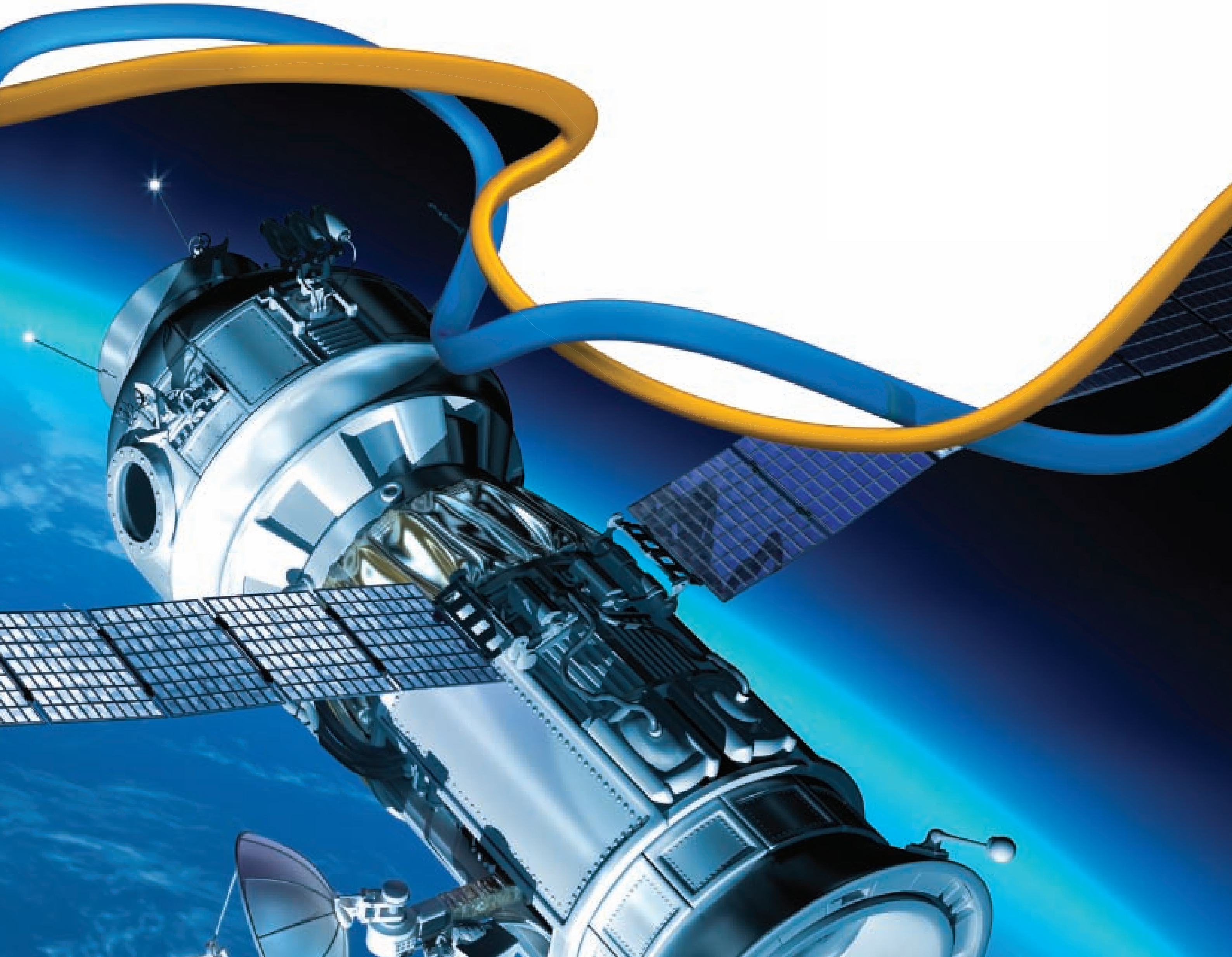
ROYAL ACADEMY OF ENGINEERING

Extreme space weather:
impacts on engineered systems and infrastructure



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This report is available online at **www.raeng.org.uk/spaceweather**

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Foreword

An extreme space weather event, or solar superstorm, is one of a number of potentially high impact, but low probability natural hazards. In response to a growing awareness in government, extreme space weather now features as an element of the UK National Risk Assessment.

In identifying this hazard, the UK government benefitted from the country's world class scientific expertise and from a number of earlier studies conducted in the US. However, the consequential impact on the UK's engineering infrastructure - which includes the electricity grid, satellite technology and air passenger safety – has not previously been critically assessed. This report addresses that omission by bringing together a number of scientific and engineering domain experts to identify and analyse those impacts. I believe that this study, with its strong engineering focus, is the most extensive of its type to date.

It is my hope that by acting on the recommendations in this report, stakeholders will progressively mitigate the impact of the inevitable solar superstorm.

Professor Paul Cannon FREng
Chair of the study working group

1. Executive summary

Rarely occurring solar superstorms generate X-rays and solar radio bursts, accelerate solar particles to relativistic velocities and cause major perturbations to the solar wind. These environmental changes can cause detrimental effects to the electricity grid, satellites, avionics, air passengers, signals from satellite navigation systems, mobile telephones and more. They have consequently been identified as a risk to the world economy and society. The purpose of this report is to assess their impact on a variety of engineered systems and to identify ways to prepare for these low-probability but randomly occurring events. The report has an emphasis on the UK, but many of the conclusions also apply to other countries.

Explosive eruptions of energy from the Sun that cause minor solar storms on Earth are relatively common events. In contrast, extremely large events (superstorms) occur very occasionally – perhaps once every century or two. Most superstorms miss the Earth, travelling harmlessly into space. Of those that do travel towards the Earth, only half interact with the Earth's environment and cause damage.

Since the start of the space age, there has been no true solar superstorm and consequently our understanding is limited. There have, however, been a number of near misses and these have caused major technological damage, for example the 1989 collapse of part of the Canadian electricity grid. A superstorm which occurred in 1859, now referred to as the 'Carrington event' is the largest for which we have measurements; and even in this case the measurements are limited to perturbations of the geomagnetic field. An event in 1956 is the highest recorded for atmospheric radiation with August 1972, October 1989 and October 2003 the highest recorded radiation events measured on spacecraft.

How often superstorms occur and whether the above are representative of the long term risk is not known and is the subject of important current research. The general consensus is that a solar superstorm is inevitable, a matter not of 'if' but 'when?'. One contemporary view is that a Carrington-level event will occur within a period of 250 years with a confidence of ~95% and within a period of 50 years with a confidence of ~50%, but these figures should be interpreted with considerable care.

Mitigation of solar superstorms necessitates a number of technology-specific approaches which boil down to engineering out as much risk as is reasonably possible, and then adopting operational strategies to deal with the residual risk. In order to achieve the latter, space and terrestrial sensors are required to monitor the storm progress from its early stages as enhanced activity on the Sun through to its impact on Earth. Forecasting a solar storm is a challenge, and contemporary techniques are unlikely to deliver actionable advice, but there are growing efforts to improve those techniques and test them against appropriate metrics. Irrespective of forecasting ability, space and terrestrial sensors of the Sun and the near space environment provide critical space situational awareness, an ability to undertake post-event analysis, and the infrastructure to improve our understanding of this environment.

The report explores a number of technologies and we find that the UK is indeed vulnerable to a solar superstorm, but we also find that a number of industries have already mitigated the impact of such events. In a 'perfect storm' a number of technologies will be simultaneously affected which will substantially exacerbate the risk. Mitigating and maintaining an awareness of the individual and linked risks over the long term is a challenge for government, for asset owners and for managers.

Space weather: impacts on engineered systems – a summary is a shortened version of this report suitable for policy makers and the media – see **www.raeng.org.uk/spaceweathersummary**.

Key points:

Solar superstorm environment

The recurrence statistics of an event with similar magnitude and impact to a Carrington event are poor, but improving. Various studies indicate that a recurrence period of 1-in-100 to 200 years is reasonable and this report makes assessments of the engineering impact based on an event of this magnitude and return time. If further studies provide demonstrable proof that larger events do occur – perhaps on longer timescales - then a radical reassessment of the engineering impact will be needed. The headline figure of 100 years should not be a reason to ignore such risks.

Electricity grid

The reasonable worst case scenario would have a significant impact on the national electricity grid. Modelling indicates around six super grid transformers in England and Wales and a further seven grid transformers in Scotland could be damaged through geomagnetic disturbances and taken out of service. The time to repair would be between weeks and months. In addition, current estimates indicate a potential for some local electricity interruptions of a few hours. Because most nodes have more than one transformer available, not all these failures would lead to a disconnection event. However, National Grid's analysis is that around two nodes in Great Britain could experience disconnection.

Satellites

Some satellites may be exposed to environments in excess of typical specification levels, so increasing microelectronic upset rates and creating electrostatic charging hazards. Because of the multiplicity of satellite designs in use today there is considerable uncertainty in the overall behaviour of the fleet but experience from more modest storms indicates that a degree of disruption to satellite services must be anticipated. Fortunately the conservative nature of spacecraft designs and their diversity is expected to limit the scale of the problem. Our best engineering judgement, based on the 2003 storm, is that up to 10% of satellites could experience temporary outages lasting hours to days as a result of the extreme event, but it is unlikely that these outages will be spread evenly across the fleet since some satellite designs and constellations would inevitably prove more vulnerable than others. In addition, the significant cumulative radiation doses would be expected to cause rapid ageing of many satellites. Very old satellites might be expected to start to fail in the immediate aftermath of the storm while new satellites would be expected to survive the event but with higher risk thereafter from incidence of further (more common) storm events. Consequently, after an extreme storm, all satellite owners and operators will need to carefully evaluate the need for replacement satellites to be launched earlier than planned in order to mitigate the risk of premature failures.

Aircraft passenger and crew safety

Passengers and crew airborne at the time of an extreme event would be exposed to an additional dose of radiation estimated to be up to 20 mSv, which is significantly in excess of the 1 mSv annual limit for members of the public from a planned exposure and about three times as high as the dose received from a CT scan of the chest. Such levels imply an increased cancer risk of 1 in 1,000 for each person exposed, although this must be considered in the context of the lifetime risk of cancer, which is about 30%. No practical method of forecast is likely in the short term since the high energy particles of greatest concern arrive at close to the speed of light. Mitigation and post event analysis is needed through better onboard aircraft monitoring. An event of this type would generate considerable public concern.

Ground and avionic device technology

Solar energetic particles indirectly generate charge in semiconductor materials, causing electronic equipment to malfunction. Very little documentary evidence could be obtained regarding the impact of solar energetic particles on ground infrastructure and it is consequently difficult to extrapolate to a solar superstorm. More documentary evidence of normal and storm time impacts is available in respect to avionics - no doubt because the operating environment has a higher flux of high-energy particles. Our estimate is that during a solar superstorm the avionic risk will be ~1,200 times higher than the quiescent background risk level and this could increase pilot workload. We note that avionics are designed to mitigate functional failure of components, equipment and systems and consequently they are also partially robust to solar energetic particles.

Global navigation satellite systems (GNSS)

Assuming that the satellites – or enough of them – survived the impact of high energy particles, we anticipate that a solar superstorm might render GNSS partially or completely inoperable for between one and three days. The outage period will be dependent on the service requirements. For critical timing infrastructure it is important that holdover oscillators be deployed capable of maintaining the requisite performance for these periods. UK networked communications appear to meet this requirement. There will be certain specialist applications where the loss or reduction in GNSS services would be likely to cause operational problems; these include aircraft and shipping. Today, the aircraft navigation system is mostly backed up by terrestrial navigation aids; it is important that alternative navigation options remain available in the future.

Cellular and emergency communications

This study has concluded that the UK's commercial cellular communications networks are much more resilient to the effects of a solar superstorm than those deployed in a number of other countries (including the US) since they are not reliant on GNSS timing. In contrast, the UK implementation of the Terrestrial European Trunked Radio Access (TETRA) emergency communications network is dependent on GNSS. Consequently, mitigation strategies, which already appear to be in place, are necessary.

High frequency (HF) communications

HF communications is likely to be rendered inoperable for several days during a solar superstorm. HF communications is used much less than it used to be; however, it does provide the primary long distance communications bearer for long distance aircraft (not all aircraft have satellite communications and this technology may also fail during an extreme event). For those aircraft in the air at the start of the event, there are already well-defined procedures to follow in the event of a loss of communications. However, in the event of a persistent loss of communications over a wide area, it may be necessary to prevent flights from taking off. In this extreme case, there does not appear to be a defined mechanism for closing or reopening airspace once communications have recovered.

Mobile satellite communications

During an extreme space weather event, L-band (~1.5GHz) satellite communications might be unavailable, or provide a poor quality of service, for between one and three days owing to scintillation. The overall vulnerability of L-band satellite communications to superstorm scintillation will be specific to the satellite system. For aviation users the operational impact on satellite communications will be similar to HF.

Terrestrial broadcasting

Terrestrial broadcasting would be vulnerable to secondary effects, such as loss of power and GNSS timing.

> *OUR ESTIMATE IS THAT DURING A SOLAR SUPERSTORM THE AVIONIC RISK WILL BE ~1,200 TIMES HIGHER THAN THE QUIESCENT BACKGROUND RISK LEVEL AND THIS COULD INCREASE PILOT WORKLOAD.*

Recommendations

A number of detailed recommendations are included in each chapter. Some of the most important are set out below. It is vital that a lead government department or body is identified for each of these recommendations.

Policy

The report makes two key policy recommendations. These are that:

1. A UK Space Weather Board should be initiated within government to provide overall leadership of UK space weather activities. This board must have the capacity to maintain an overview of space weather strategy across all departments.
2. The Engineering and Physical Sciences Research Council (EPSRC) should ensure that its own programmes recognise the importance of extreme space weather mitigation and EPSRC should be fully integrated into any research council strategy.

Solar superstorm environment

3. The UK should work with its international partners to further refine the environmental specification of extreme solar events and where possible should extend such studies to provide progressively better estimates of a reasonable worst case superstorm in time scales of longer than ~200 years.

Electricity grid

4. The current National Grid mitigation strategy should be continued. This strategy combines appropriate forecasting, engineering and operational procedures. It should include increasing the reserves of both active and reactive power to reduce loading on individual transformers and to compensate for the increased reactive power consumption of transformers.

Satellites

5. Extreme storm risks to space systems critical to social and economic cohesion of the country (which is likely to include navigation satellite systems) should be assessed in greater depth. Users of satellite services which need to operate through a superstorm should challenge their service providers to determine the level of survivability and to plan mitigation actions in case of satellite outages (eg network diversification).

Aircraft passenger and crew safety

6. Consideration should be given to classifying solar superstorms as radiation emergencies in the context of air passengers and crew. If such a classification is considered appropriate an emergency plan should be put in place to cover such events. While the opportunities for dose reduction may be limited, appropriate reference levels should be considered and set, if appropriate.

Ground and avionic device technology

7. Ground-and space-derived radiation alerts should be provided to aviation authorities and operators. The responsible aviation authorities and the aviation industry should work together to determine if onboard monitoring could be considered a benefit in flight. Related concepts of operation should be developed to define subsequent actions; this could even include reductions in altitude if deemed beneficial and cost-effective.

Global navigation satellite systems (GNSS)

8. All critical infrastructure and safety critical systems that require accurate GNSS derived time and or timing should be specified to operate with holdover technology for up to three days.

Terrestrial mobile communication networks

9. All terrestrial mobile communication networks with critical resiliency requirements should also be able to operate without GNSS timing for periods up to three days. This should particularly include upgrades to the network including those associated with the new 4G licenses where these are used for critical purposes and upgrades to the emergency services communications networks.

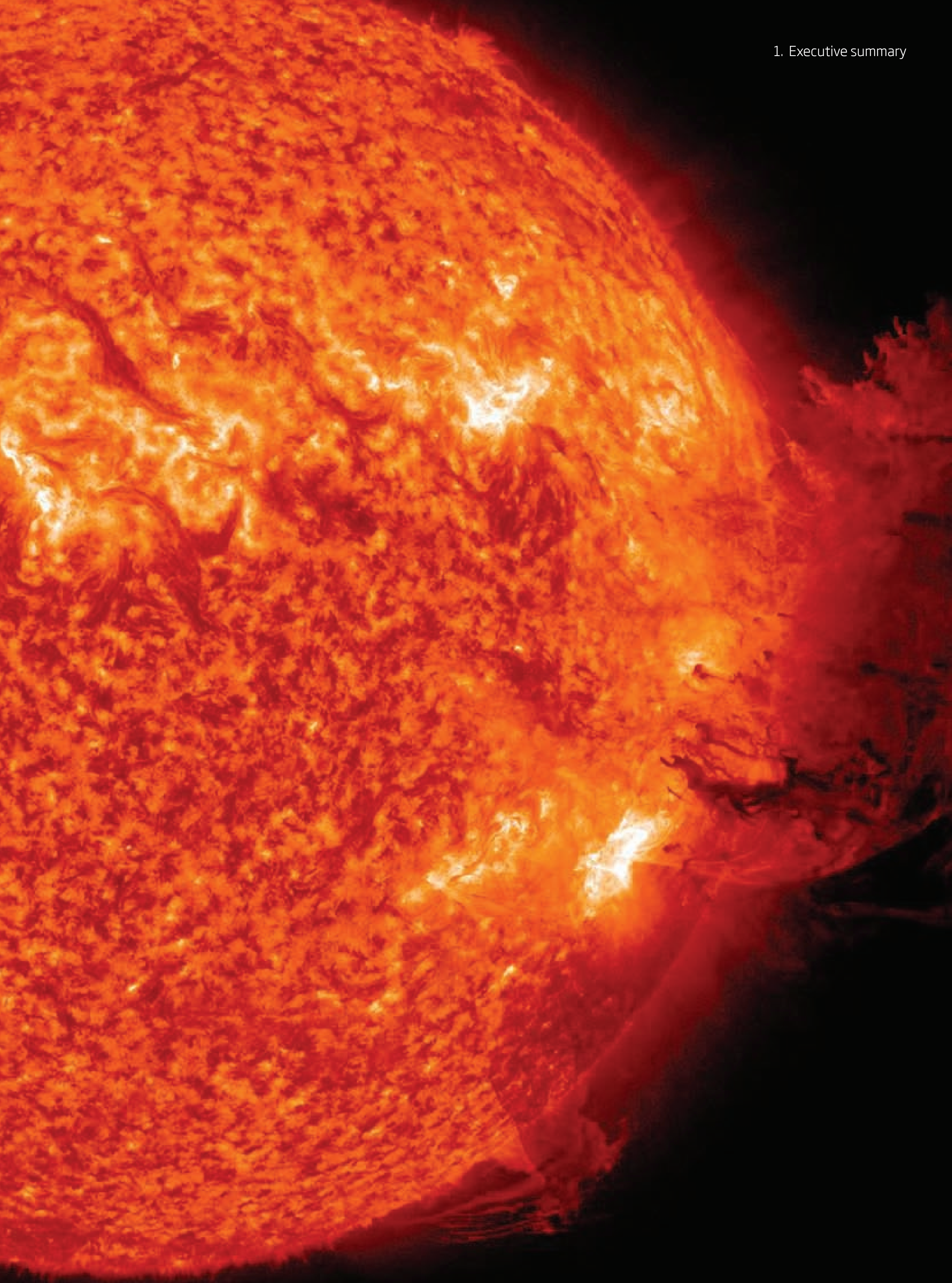
High frequency (HF) communications

10. The aviation industry and authorities should consider upgrades to HF modems (similar to those used by the military) to enable communications to be maintained in more severely disturbed environments. Such an approach could significantly reduce the period of signal loss during a superstorm and would be more generally beneficial.

Terrestrial broadcasting

11. Where terrestrial broadcasting systems are required for civil contingency operations, they should be assessed for vulnerabilities to the loss of GNSS timing.

The Sun unleashed an M-2 (medium-sized) solar flare, an S1-class radiation storm and a spectacular coronal mass ejection (CME) on 7 June 2011 © NASA



2. Introduction

2.1 Background

The April 2010 Icelandic (Eyjafjallajökull) volcano eruption and resulting ash cloud and the March 2011 Japanese earthquake and tsunami demonstrated how devastating rarely occurring natural hazards can be to society and national economies. Natural events have no respect for national boundaries and *in extremis* the whole world can suffer.

In 2011, the UK recognised extreme space weather events (also referred to as solar superstorms and sometimes simply as superstorms) as one such rare, but high impact, hazard. Space weather was for the first time included as part of the UK National Risk Assessment (NRA) – an unclassified version of which can be found at: **www.cabinetoffice.gov.uk/resource-library/national-risk-register.**

The Royal Academy of Engineering has sought, through this study, to articulate the potential engineering impact of such events, particularly in a UK context.

This report seeks to describe the effects, evaluate the impact and advise on suitable mitigation strategies, but has not deliberated on societal or economic impacts. Above all the report seeks to be realistic in terms of the engineering impacts so that solar storms can be better placed in the context of other natural hazards.

2.2 Scope

This study has involved understanding the operational threats posed by extreme space weather on a number of ground, air and space-based technologies and then understanding how these technologies respond to those threats. The report has benefited from an earlier US workshop report [*NRC*, 2008].

The report addresses:

- induced currents on the electrical grid, railways, telecommunication-wirelines and other networks
- charging and ageing effects on spacecraft
- drag effects on spacecraft orbits
- radiation doses for aircrew and passengers
- unwanted upsets in sophisticated electronics on aircraft and on the ground
- a wide variety of effects on radio technologies, including navigation and communication.

The report makes recommendations intended to improve the understanding of extreme events and to help to mitigate their effects. The report does not consider high altitude nuclear explosions or any other manmade modifications of space weather. A summary report has also been published and is available at **www.raeng.org.uk/spaceweathersummary**.

3. Space weather

3.1 Introduction

Space weather is a term which describes variations in the Sun, solar wind, magnetosphere, ionosphere, and thermosphere, which can influence the performance and reliability of a variety of space-borne and ground-based technological systems and can also endanger human health and safety [*Koons et al.*, 1999]. Many of the systems affected by space weather are illustrated in *Figure 1*; just like terrestrial weather, space weather is pervasive and compensating for its impact is a challenge.

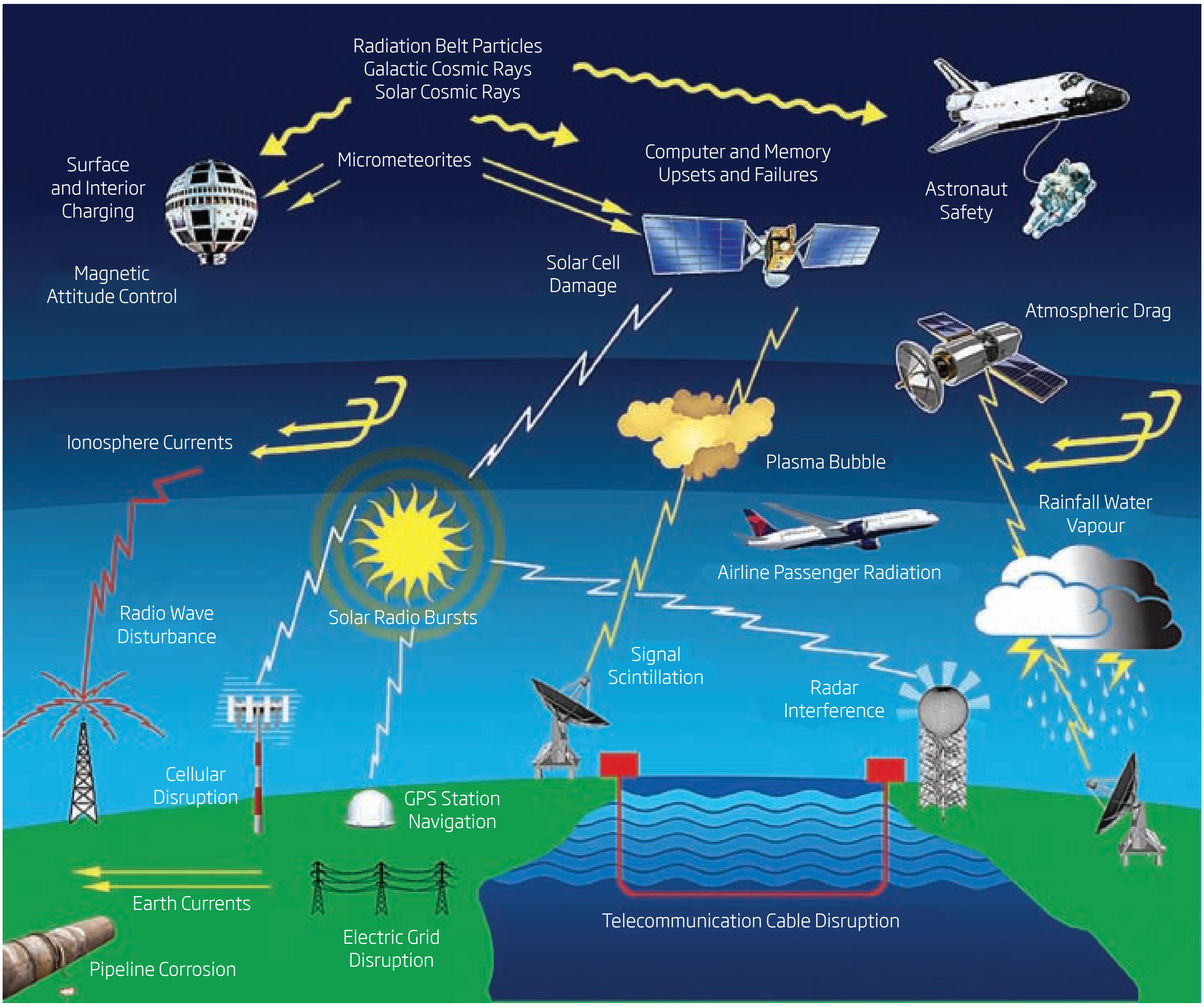
Space weather exhibits a climatology which varies over timescales ranging from days (ie diurnal variations resulting from the rotation of the Earth) to the 11-year solar cycle and longer periods such as grand solar maxima and minima [*Lockwood et al.*, 2012].

Superimposed on this climatology are weather-like variations; on some days space weather is more severe than on others. Minor solar storms are relatively common events; in contrast, extremely large events (superstorms) occur very occasionally – perhaps once every century or two.

3.2 Causes of space weather

Although there is some influence from outside the solar system, most space weather starts at the Sun. The elements of the coupled Sun-Earth space weather system consist of Sun, solar wind, solar magnetic field, magnetosphere and ionosphere, as displayed in *Figure 2*.

Figure 1: Impacts of space weather © L. J. Lanzerotti, Bell Laboratories, Lucent Technologies, Inc.



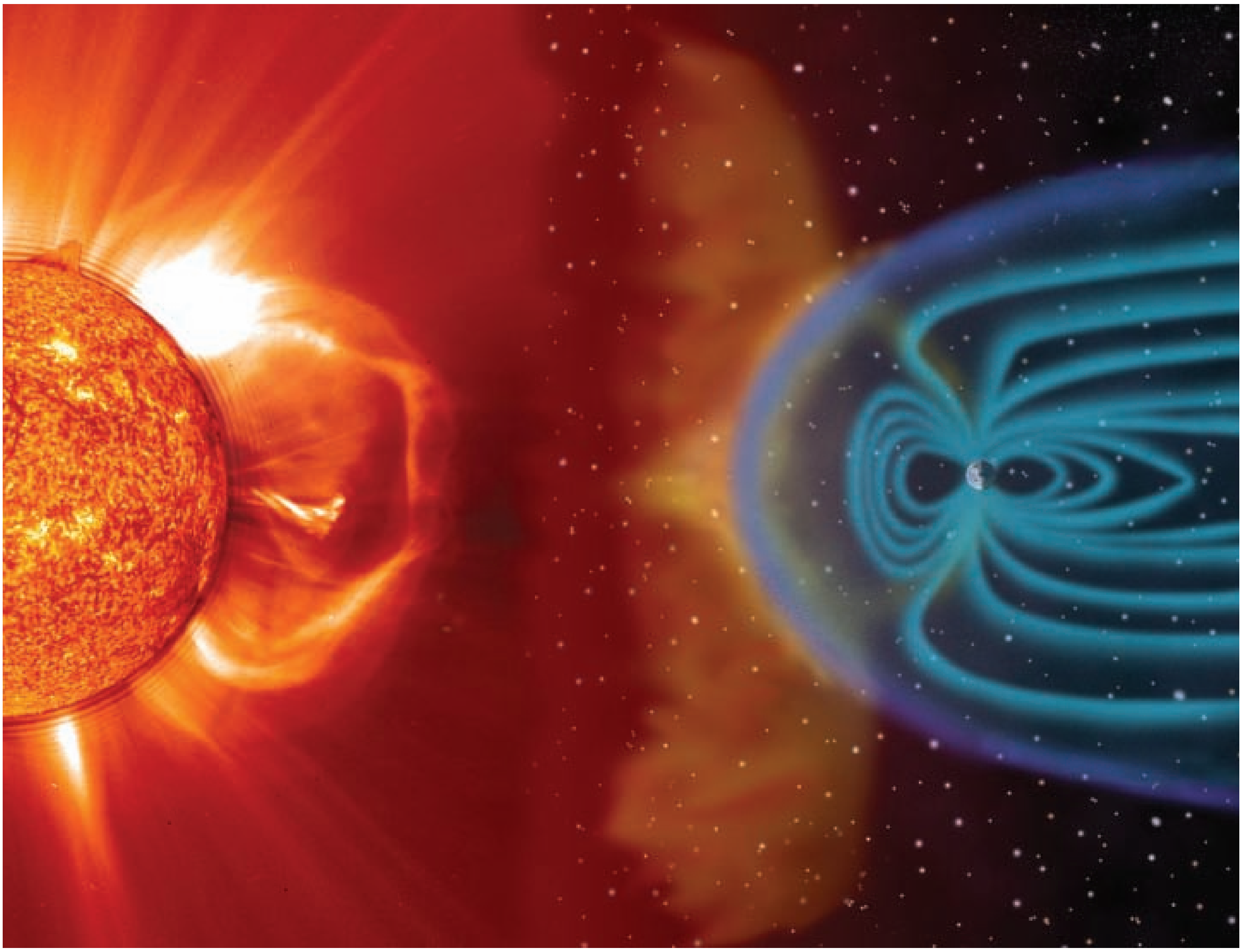


Figure 2: The space weather environment © NASA

The Sun is a nearly constant source of optical and near-infrared radiation. However, there is considerable variability during storm periods at EUV, X-ray and radio wavelengths. During these periods, the Sun is also more likely to generate high-energy solar energetic particles (SEPs) and the solar wind plasma speed and density, forming part of the solar corona, can increase substantially. Coronal mass ejections (CMEs) are one manifestation of the latter and stream interaction regions (SIRs), formed when fast streams in the solar wind overtake and compress slow streams, also occur. Directly or indirectly the ionising radiation, the ionised particles and the plasma interact with the magnetosphere and the ionosphere below it to cause a variety of effects on engineered systems.

The orientation of the interplanetary magnetic field (IMF) in the solar wind controls the degree to which CMEs and SIRs influence the magnetosphere-ionosphere system, producing the disturbances that we call geomagnetic storms. When the IMF has a southward-pointing component, magnetic reconnection (or merging) between the IMF and the Earth's magnetic field occurs on the dayside of the magnetosphere and allows solar wind energy to enter the magnetosphere. Only then is the solar event said to be geoeffective. When a geoeffective event occurs, the energy abstracted from the solar wind is transported to the nightside of the Earth and temporarily stored in the tail of the magnetosphere. When the stored energy reaches some critical level, it is released explosively by magnetic reconnection and some of that energy is directed towards Earth. This cycle of energy storage and release is called a substorm and typically has a period of one to two hours; it will be repeated as long as solar wind energy enters the magnetosphere. For the purpose of this report, the key point to note is that a geomagnetic storm contains a series of a substorms, so many of the effects described in this report will come in a series of pulses and not as a continuous period of high activity.

Extreme space weather is thought to be associated with fast (>800 km s^{-1}) CMEs, which are preceded by a shock wave that

THE SUN IS A NEARLY CONSTANT SOURCE OF OPTICAL AND NEAR-INFRARED RADIATION. HOWEVER, THERE IS CONSIDERABLE VARIABILITY DURING STORM PERIODS AT EUV, X-RAY AND RADIO WAVELENGTHS.

compresses the ambient solar wind plasma and magnetic field (typically by a factor of four). This sharply accelerates the solar wind velocity with respect to Earth and introduces a sharp deflection in the direction of the magnetic field. This shock is also a strong source of SEPs. The so-called sheath region between the shock and the CME contains both high speed solar wind and a strong magnetic field. If the deflection of that magnetic field is strongly southward, the CME sheath can initiate severe geomagnetic storms.

During periods of high solar activity, the Sun can launch several CMEs towards Earth and these may collide during their transit to Earth. This is not unusual since the first CME may be slowed down as it sweeps up the ambient solar wind in its sheath, leaving behind a low density region that allows a following CME to catch up. The result is to produce a more complex pattern of IMF changes as the combined CMEs pass the Earth, driving a longer series of substorms and hence a longer, more intense geomagnetic storm.

3.3 The geomagnetic environment

The Earth's magnetic field comprises contributions from sources in the Earth's core, the lithosphere (ie crust and upper mantle), the ionosphere, the magnetosphere and also from electrical currents coupling the ionosphere and magnetosphere ('field aligned currents', or FAC). The sources external to the solid Earth also induce secondary fields in the Earth (*Figure 3*).

To a first approximation the geomagnetic field is similar to that of a dipole (or bar magnet) currently inclined at around 11 degrees to the geographic poles. The core field is generated by dynamo action in which the iron-rich fluid outer core convects as a result of the heat sources contained within it. This fluid convection across existing magnetic field lines generates electrical currents that generate, in turn, further magnetic fields, with diffusion losses counteracting the generation of new magnetic field. The dynamics of field generation and diffusion provide a spatially and temporally complicated magnetic field pattern across the Earth and in space.

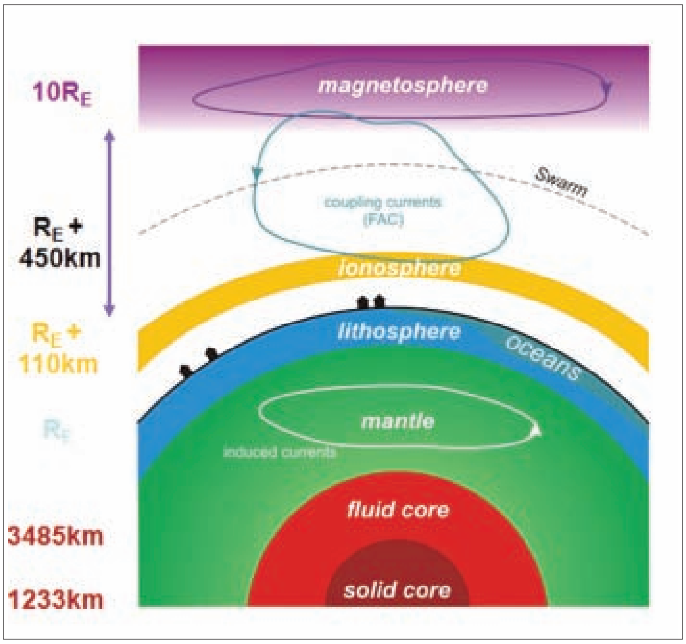


Figure 3: The geomagnetic environment. 'RE' indicates one Earth radius (6372 km). The dotted line and the building silhouettes indicate, respectively, measurement platforms in orbit and at permanent ground-based magnetic observatories © DTU Space, Technical University of Denmark

The core field is the dominant component of the measured field (of order 90% of the field strength) near the Earth's surface and in near-Earth space. Changes in the core field occur on timescales of months to millennia and can include 'reversals', where the polarity (North or South) of the magnetic poles reverses. Reversals occur on average every 200,000 to 300,000 years and take a few thousand years to complete once the process begins. The lithospheric field is stable, except on geological timescales, and is the consequence of the presence of rocks rich in magnetic minerals. Lithospheric fields contribute up to 5% of the measured field near the surface, but can be very large near localised crustal magnetic anomalies.

The ionospheric, magnetospheric and FAC magnetic sources producing the external magnetic field are controlled by solar UV- and X-ray radiation, the solar wind and solar magnetic activity. The dynamics of these magnetic fields reflect the variability of space weather. Rapid time variations in these external electrical current systems induce surface electric fields in the Earth that can drive geomagnetically induced currents (GIC) through grounded conducting networks, such as electricity, pipeline and railway grids. External field variations can reach 5-10% of the total magnetic field at the Earth's surface during geomagnetic storms caused by space weather.

3.4 The satellite environment

The satellite high-energy radiation environment derives from three sources:

- galactic cosmic rays (GCR) from outside the solar system
- solar energetic particles (SEP) accelerated near the Sun by shock waves
- radiation belt particles trapped inside the Earth's magnetic field.

The Earth is subjected to a continuous flux of GCRs generated by supernovae explosions throughout the galaxy. These are very energetic protons, helium nuclei and heavier ions and are modulated by the solar wind and the interplanetary magnetic field. Typically, the flux varies by a factor of two over the eleven-year solar cycle and is highest during periods of low solar activity. It also varies markedly as large CMEs pass the Earth and block the propagation of cosmic rays – an effect now being explored as an additional way to detect CMEs. Cosmic rays cause single event effects, damage to electronic components and degradation of solar array power. The variation in galactic cosmic rays is generally understood and predictable and is not directly relevant to this discussion on extreme events.

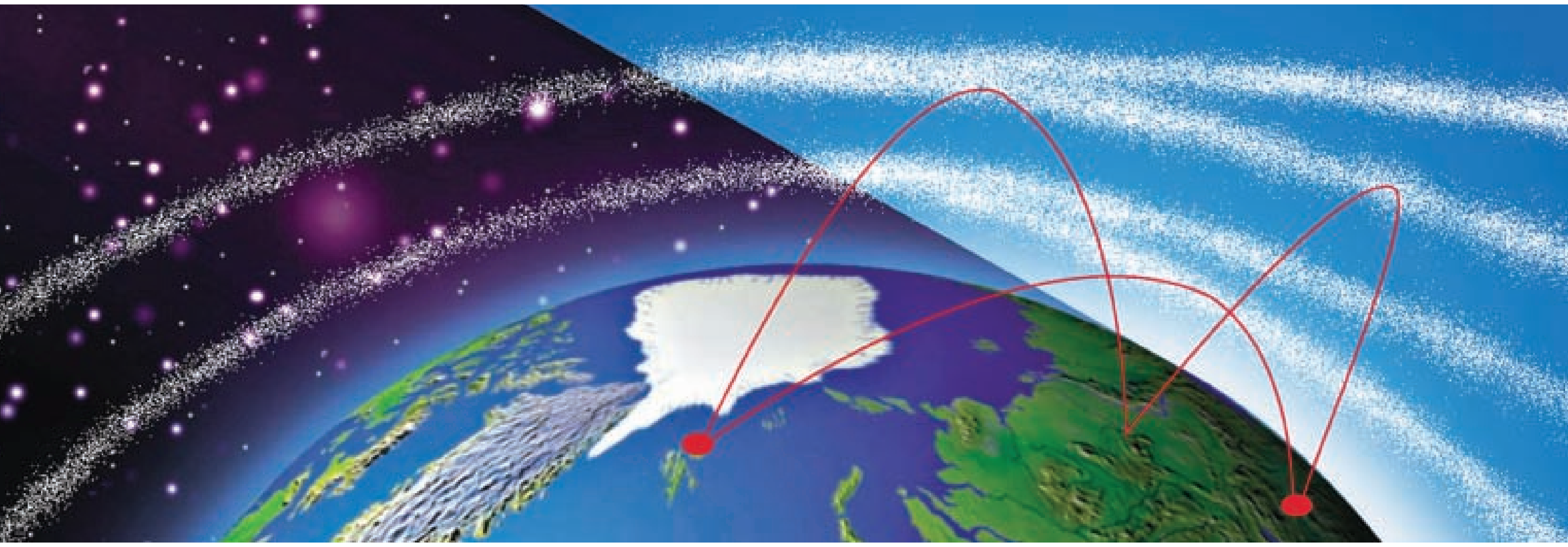
SEPs are very high-energy ions, mainly protons which are so energetic that the first particles take only a few minutes to reach the Earth. They are accelerated close to the Sun by both rapidly changing magnetic fields and by shock waves in the solar wind. The former are thought to produce short-lived (≤1 day) impulsive events while the latter produce much longer (gradual) events [*Reames*, 1999]. Predicting how long gradual events will last is very difficult as it depends on the evolution of the CME shock wave as it travels away from the Sun, and on how well the shock is connected to the Earth via the interplanetary magnetic field; this varies in direction but favours events originating at around 45° West on the Sun. These events often exhibit a peak in SEP fluxes as the shock passes the Earth.

The Earth's magnetosphere partly shields the Earth against GCRs and SEPs but they have easier access near the magnetic poles than at the equator. The geomagnetic shielding falls off with spacecraft altitude and during extreme events the shielding at all orbits can become greatly reduced as the magnetopause is pushed close to or inside this orbit.

Changes in the radiation belts are driven by the interaction of the solar wind with the Earth's magnetosphere. The inner radiation belt (within about 2 Earth radii) consists of energetic protons and electrons while the outer radiation belt (3-7 Earth radii) is dominated by electrons. The high-energy electrons cause a range of problems for satellites, particularly satellite charging effects [*Iucci et al.*, 2005] while protons in the inner belt produce cumulative dose and damage as well as prompt single event effects. Satellites in geostationary orbit (GEO) pass through the outer edge of the radiation belts, whereas those in medium Earth orbit (MEO) pass through the heart of the outer radiation belt. Satellites in low Earth orbit (LEO) operate mainly underneath the belts, but encounter the inner radiation belt in a region known as the South Atlantic Anomaly. LEO satellites that have orbits inclined more than about 50° to the Equator will, in addition, encounter the outer radiation belt in the high latitude auroral regions. High inclination LEO satellites are also vulnerable to SEPs encountered over high latitude regions.

While the inner radiation belt is fairly stable, the outer radiation belt is highly dynamic and the flux of relativistic electrons, with energies of mega-electron volts (MeV), can change by five orders of magnitude on timescales from a few hours to a few days [*Baker et al.*, 2007]. In exceptional cases, the low intensity slot region

Figure 4: Rays refracted from the layered ionosphere © QinetiQ



between the main belts has been observed to increase by orders of magnitude on a timescale of two minutes, for example on 24th March, 1991 [*Blake et al.*, 1992].

Some of the highest radiation belt electron fluxes have been observed when there is a fast solar wind stream emanating from a coronal hole on the Sun. These events occur more often during the declining phase of the solar cycle as coronal holes migrate from high latitudes towards the equator and the fast solar wind is more able to encompass the Earth.

It should be noted that, beyond geostationary orbit the Earth's magnetic field contains a reservoir of electrons at energies of 1-10 keV. Changes in the solar wind can trigger global changes in the Earth's magnetic field which rapidly transport these electrons towards the Earth in what is known as a substorm. The electrons envelop those satellites in GEO and MEO orbits mainly between midnight and dawn, causing surface charging, changes in the satellite potential and degradation of satellite surface materials [*Koons and Fennell*, 2006]. The injected electrons also penetrate along the magnetic field to low altitudes and affect polar orbiting satellites in LEO at high latitudes.

3.5 Atmospheric radiation environment

When galactic cosmic rays (GCRs) strike the atmosphere they can interact with the nuclei of oxygen and nitrogen molecules to generate a cascade of secondary particles including neutrons, protons and electrons. The secondary radiation builds up to a maximum at around 60000 feet (18 km) and then attenuates down to sea level. The fluxes of particles at subsonic flight levels (12 km) are some 300 times greater than at sea level while at 18 km they are about 500 times more intense. The geomagnetic field provides greater shielding at the equator than at the poles and the secondary radiation increases by about a factor of five between the equator and latitudes of around 60 degrees beyond which the levels flatten off with increasing latitude.

SEPs also contribute to the atmospheric radiation environment. They vary greatly in energy spectrum but approximately once a year the particles are sufficiently energetic to increase the flux of secondary neutrons measured on the ground. This is known as a ground level event (or GLE) but is also associated with significant increases in radiation at aircraft cruising altitudes.

> *WHEN GALACTIC COSMIC RAYS (GCRS) STRIKE THE ATMOSPHERE THEY CAN INTERACT WITH THE NUCLEI OF OXYGEN AND NITROGEN MOLECULES TO GENERATE A CASCADE OF SECONDARY PARTICLES INCLUDING NEUTRONS, PROTONS AND ELECTRONS.*

3.6 Ionospheric environment

The ionosphere (*Figure 4*) is a lightly ionised region of the upper atmosphere that extends from about 60 to 2,000 km in altitude with a density peak around 300km altitude.

The Sun emits electromagnetic waves over a range of frequencies and the maximum intensity of the spectrum occurs in the visible range. However, it is primarily the extreme ultraviolet and soft X-ray portions of the spectrum that produce the ionosphere, with additional contributions from electron precipitation in the auroral region and ionisation by SEPs in the polar cap region.

The solar photo-ionising radiation is attenuated by the atmosphere, with the more energetic radiation penetrating further into the atmosphere. Each atmospheric chemical species has a distinct photo-ionisation energy and consequently different species are preferentially ionised at different altitudes. Recombination losses are also height dependent, and in combination with the production process, this produces defined layers of ionisation (*Figure 4*).

The ionosphere can be conventionally divided into four latitudinal regions: equatorial, mid-latitude, auroral and polar cap. The mid-latitude region (under which the UK sits during non-storm periods) is by far the least variable, both spatially and temporally.

The ionospheric plasma is conductive and, therefore, interacts with electromagnetic waves. Low-frequency radio waves are often considered to be reflected and high frequencies are refracted – sometimes so much so that the signals return to the ground as if they had been reflected. Still higher frequency signals pass through the ionosphere but are still weakly refracted and delayed. The ionosphere generally has no practical impact on signals above 2 GHz, but occasionally the effects extend to higher frequencies.

3.7 Space weather monitoring and forecasting

Monitoring

Space weather is routinely monitored by many ground and space-based instruments, operating in the optical and radio bands and via *in-situ* measurements of the local plasma. This report cannot hope to do justice to these instruments, but it worth noting the importance of the Advanced Composition Explorer (ACE) satellite

> *CME FORECASTING IS MORE TRACTABLE THAN SEP FORECASTING BECAUSE CMES TAKE MANY HOURS TO TRAVEL TO THE EARTH. IT IS NOW POSSIBLE TO MONITOR AND MODEL THE EVOLUTION OF AN EARTH-DIRECTED CME SUCH THAT ITS ARRIVAL AT EARTH CAN SOMETIMES BE FORECAST WITH AN ACCURACY OF =6-8 HOURS.*

which is located ~1.5 million kilometres towards the Sun where a stable orbit can be established around the L1 Lagrange point. Real-time data from ACE are used by various agencies to improve forecasts and warnings of solar storms as they travel between Sun and Earth. The US is planning to launch the DSCOVR satellite to L1 in 2014 to act as a backup for ACE. Looking to the longer term a Chinese satellite, Kuafu, may also be placed at the L1 point in the year 2017 while the ESA Space Situational Awareness programme is planning an L1 monitor for launch ahead of the 2024 solar maximum.

Solar monitoring is critical to forewarning of solar events that could generate severe space weather at Earth – it enables engineering teams to go on standby and it helps provide the context against which scientific advice and political decisions can be made. Unfortunately, solar wind monitoring at the L1 point provides only 15 to 30 minutes' warning in regards to CME-related effects which dominate many of the most important impacts of a superstorm. Thus, there is growing interest in improving this warning time by a number of methods. Placing a monitor further upstream using solar sail technology is one option and to explore this NASA will fly a demonstration mission, Sunjammer, in 2015. The UK Space Agency has recently approved funding for UK teams to fly a magnetometer and plasma sensor on this mission. Other options include remote sensing of the interplanetary magnetic field using radio telescopes to make Faraday rotation measurements; and better modelling of the magnetic field topology in the Sun's atmosphere and the inner heliosphere (a requirement that is now recognised as a crucial scientific step in understanding all aspects of solar activity). The UK scientific community is strongly engaged in all of these activities.

Forecasting

Electromagnetic and SEP-related effects will always be difficult to forecast since the effects travel at or close to the speed of light. Predicting the time of a solar eruption is not currently possible, though there are services that forecast the probabilities of classes of flares and SEPs.

To overcome this fundamental physical limitation flare forecasting will need to be based on identifying precursor features [e.g. *Ahmed et al.*, 2011]. For SEPs, options include forecasts based on flare observations [e.g. *Laurenza et al.*, 2009; *Núñez*, 2011] and on observations of SEP electrons that reach Earth ahead of the more dangerous SEP ions [*Posner*, 2007]. For some of these experimental techniques to transition to an operational capability, it will be necessary to monitor plasma structures and magnetic fields across the whole surface of the Sun including the far side.

There has also been significant progress in recent years towards forecasting the energy spectrum of related SEP events – which is critical to assessing their consequences. This progress reflects the growing use of hybrid and full-kinetic models to simulate particle energisation, particularly at the shock waves ahead of fast CMEs, and the availability of adequate computing power to run those models. However, this approach is fundamentally dependent on knowledge of the shape and Mach number of the shock and thus dependent on progress in monitoring and modelling CME propagation.

CME forecasting is more tractable than SEP forecasting because CMEs take many hours to travel to the Earth. It is now possible to monitor and model the evolution of an Earth-directed CME such that its arrival at Earth can sometimes be forecast with an accuracy of ±6-8 hours [*Taktakishvili et al.*, 2010]. Unfortunately, these errors are larger for fast CMEs which would be expected during a superstorm. Furthermore, forecasts of its geoeffectiveness are currently not possible until the CME reaches the L1 point, where its magnetic field can be measured and alerts issued to engineering teams and agencies. The lead time is then only 15-30 minutes. That warning time would be significantly increased if the CME magnetic field could be determined upstream from L1.

3.8 Space weather forecasting - summary and recommendations

Summary

Space weather monitoring is critical to forewarning of solar events that could generate severe space weather at Earth. It enables engineering teams to go on standby and it helps provide the context against which scientific advice and political decisions can be made.

Forecasts provide another useful capability which, given sufficient accuracy, could change how space weather is mitigated. Currently neither flares nor SEPs can be forecast but there are techniques in research that may improve this situation. Operational provision of such a service would necessitate the appropriate instrumentation including monitoring of the far side of the sun.

CME arrival time can be forecast with an arrival time accuracy of ±6-8 hours which, although far from precise, is useful for putting the engineering teams on standby; this can be expected to improve over the next few years. However, the geoeffectiveness of the CME cannot be judged and definitive forecasts issued until the CME reaches the L1 point satellite sensor, thereby providing only 15-30 minute notice.

Recommendations

- The UK should work with its international partners to ensure that a satellite is maintained at the L1 Lagrangian point, and that data from the satellite is disseminated rapidly.
- The UK should work with its international partners to explore innovative methods to determine the state of the solar wind, and its embedded magnetic field upstream from L1.
- The UK should work with its international partners to ensure the continued provision of a core set of other space-based measurements for monitoring space weather.

4. Solar superstorms

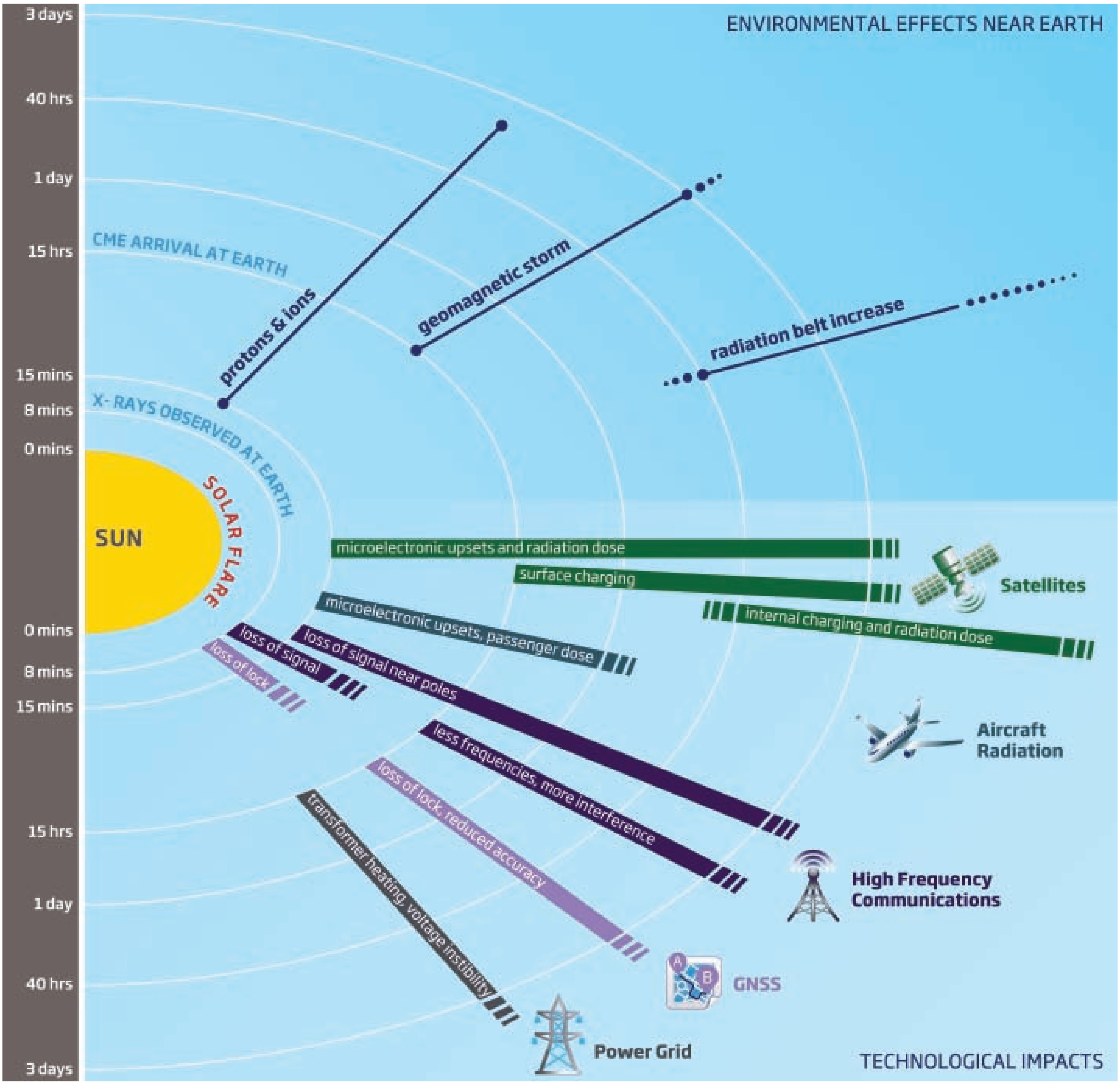
4.1 Outline description

As already described, the geomagnetic, satellite, atmospheric radiation and ionospheric environments all react to increased solar activity. However, each environment reacts differently depending on the energy spectrum of the electromagnetic and particle radiation.

Solar storms all differ, yet we understand their basic chronology and their consequences (*Figure 5*)

- The storm starts with the development of one or more complex sunspot groups which are observed to track across the solar surface.
- From within these active regions, one or more solar flares occur and are detected on Earth at radio, optical and x-ray wavelengths just eight minutes later.
- Highly solar energetic (relativistic) particles are released and detected just a few minutes later on both satellites and on the ground. These continue to arrive over a period of hours and even days if further eruptions occur.

Figure 5: A summary of space weather effects on technology © Royal Academy of Engineering 2012



- A coronal mass ejection of plasma occurs which travels outwards at many hundred kilometres per second, taking ~ 15-72 hours to arrive at the orbital distance of the Earth. The level of impact on Earth is dependent on the speed of the CME, how close it passes with respect to Earth, and the orientation of the magnetic fields in the CME and in the compressed solar wind ahead of the CME.

4.2 The history of large solar storms and their impact

The effects of solar storms [*Baker*, 2002; *Baker and Green*, 2011] can be measured in a number of ways but the longest series of measurements (since the 1840s) has been made by ground-based magnetometers. These records have demonstrated that there have been many solar storms of which a very small number are severe (*Figure 6*). The storm of 2-3 September 1859 is the largest event on record and is known as the Carrington event, after Richard Carrington, the distinguished British astronomer who observed a huge solar flare on the day before the storm. During this period aurora were seen all over the world, rather than just at high latitudes, with contemporary reports of aurora in the Caribbean. The Carrington event serves as the reference for many studies and impact assessments.

We now believe that this flare was associated with a very fast CME that took only 17.6 hours to travel from the Sun to the Earth. The Carrington event has been widely studied in the past decade [e.g. *Clauer and Siscoe*, 2006 and references therein] and we now have a wealth of published data and analyses. These suggest that the Earth was hit by a CME travelling at about 1900 km s^{-1} and with a large southward-pointing magnetic field (100 to 200 nT) in the sheath of compressed plasma just ahead of the CME (but behind its shock wave). It is this combination of high speed and strong southward magnetic field that generated such a severe geomagnetic storm because it allowed the energy of the CME to enter the Earth's magnetosphere [*Tsurutani et al.*, 2003]. The location and duration of the impact region depends on processes in Earth's magnetosphere and upper atmosphere, in particular the substorm cycle previously discussed. This extracts energy from the solar wind, stores it as magnetic energy in the tail of Earth's magnetosphere and then explosively releases it back towards the Earth. During a severe geomagnetic storm, such as the Carrington event, lasting one or more days, there will be many substorms at intervals of one to three hours. Each substorm will produce severe conditions that will often be localised in space and time.

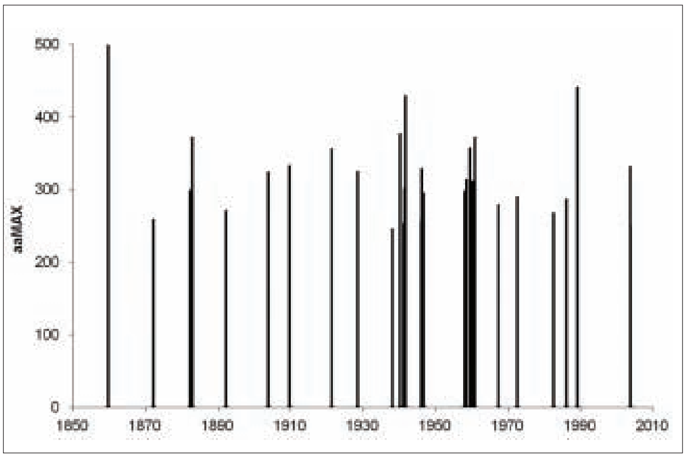


Figure 6: The top 31 geomagnetic storms since 1850; storm sizes based on the geomagnetic index, aa*MAX index developed at the US National Geophysical Data Center (for more background see Annex A of Hapgood [2011]). The Carrington event is the large peak on the left © Rutherford Appleton Laboratory

There are a number of possible storm metrics. These can, for example, address the related geomagnetic storm or the radiation storm. *Figure 6* shows one measure of the most severe geomagnetic storms that have occurred over the past 170 years with the Carrington event on the far left of the figure.

Disruption of telegraph and telephone communications is well attested in descriptions of the 1859 event and by others [*Boteler*, 2006; *Boteler and van Beek*, 1999; *Stenquist*, 1914]. In one spectacular case in May 1921 a telephone exchange in central Sweden was badly damaged by a fire started by the electric currents induced by space weather [*Karsberg et al.*, 1959]. The contemporary threat to telephone systems (and now to the internet) is much reduced following the widespread use of optical fibre, rather than copper wires. Nonetheless they are a valuable historical proxy for the contemporary threats.

The space age has seen a number of major space weather events that provide further insights into extreme space weather. A prime example is the event of August 1972 which saw: (a) the fastest CME transit time on record (reaching Earth only 14.6 hours after leaving the Sun [*Cliver and Svalgaard*, 2004] (b) the most intense radiation storm of the early space age [*Barnard and Lockwood*, 2011] and (c) the magnetopause compressed to less than 20,000 km from Earth (compared to the usual 60,000 km) [*Anderson et al.*, 1974]. Yet there was only a modest geomagnetic storm (Dst ~ -120 nT). (Dst is a geomagnetic metric measured in nano-Tesla). With the scientific knowledge that we have 40 years on, it is likely that this event was similar to the Carrington event, but with a northward interplanetary magnetic field (IMF). Thus the fast CME generated an intense radiation storm and compressed the magnetosphere, but deposited only a modest amount of energy into the magnetosphere (probably through magnetic reconnection on the high latitude magnetopause, an effect that is now known to occur during northward IMF [e.g. see *Dunlop et al.*, 2009]). This event should be regarded as a near miss – a severe event whose practical impact was mitigated by a combination of northward IMF and the contemporary resilient technology.

Another significant event was the geomagnetic storm of 8-9 February 1986, which saw Dst drop to -301 nT. This event is significant because of its timing very close to sunspot minimum, which nominally occurred in September 1986, but which would have been in March 1986 if the February storm had not occurred. This storm shows that extreme events can occur at any phase of the solar cycle and it is unwise to focus mitigation efforts only around solar maximum.

The year of 1989 saw two major space weather events: (a) a huge geomagnetic storm in March and (b) a huge solar radiation storm in October. The great geomagnetic storm of 13-14 March 1989 was the largest of the modern era with Dst falling to -589 nT. It produced a wide variety of impacts including: (a) the well-documented power blackout in Quebec [*Bolduc*, 2002] as well as transformer damage in the UK [*Erinmez et al.*, 2002] and other countries; (b) the loss of positional knowledge for over 1,000 space objects for almost a week [*Air Weather Service*, 1997] and many other impacts described elsewhere in this report. The radiation storm of October 1989 was actually a series of large events all occurring within a week, thus giving a very high fluence (time-integrated flux) for particles with energies of above 60 MeV. This was nearly four times that from the 1972 radiation storm [*Barnard and Lockwood*, 2011] and in terms of fluence, it is the largest event seen so far in the space age. In terms of instantaneous flux, its peak almost matched the 1972 event.

Another much studied event is the radiation storm that occurred on 14 July 2000 (the so-called Bastille Day event) and the associated geomagnetic storm on 15-16 July. This was a smaller event than those described above: peak flux and fluence were respectively 30% and 70% of the 1972 event [*Barnard and Lockwood*, 2011] and Dst dropped to -301 nT. This event was a useful (and low-cost) wake-up call for the satellite launcher community in that the launch of the first pair of Cluster-II spacecraft was planned for that day. The launch team received warnings about the radiation storm but lacked pre-planned criteria to assess the risk. Fortunately problems with ground equipment delayed the launch until after the storm.

The last days of October 2003 saw another major space weather event (the so-called Halloween event). This was a weaker event than in 1989 (Dst fell to -383 nT, radiation fluence 60% of the 1972 event), but provided a wealth of evidence for space weather impacts [*Weaver et al.*, 2004]. In particular, it provided clear evidence that large geomagnetic storms can disrupt space based navigation systems by inducing rapid and large changes in the morphology of the ionosphere and plasmasphere. This event dominates much current experience of space weather both because it is still a recent event and because of the wealth of environmental and impact data available.

Finally we note that on 4 November 2003, a few days after the Halloween event, the Sun produced the largest X-ray solar flare observed since the advent of space measurements [*Clark*, 2007; *Thomson et al.*, 2005] – and one that was probably similar in strength to the flare associated with the CME that caused the Carrington event . Fortunately this flare occurred on the west limb of the Sun, as the region that caused the Halloween event rotated to the far side of the Sun. Significant energetic particle fluxes were detected despite the poor connection from the event on the Sun to the Earth via the interplanetary field. There has been reasonable speculation that this event would have produced a Carrington-class CME as well as intense particle fluxes but, fortunately, both missed the Earth.

4.3 Quantifying the geophysical impact

In order to judge the impact of a superstorm on a number of contemporary technologies, it is necessary to have a baseline description of the geomagnetic, electromagnetic and high-energy particle environment during a typical event. This description has been developed in the UK through the work of the Space Environment Impact Expert Group (SEIEG) and has been issued as a report [*SEIEG*, 2012]. Further iterations of this report are expected as our knowledge improves.

4.4 The environmental chronology of a superstorm

No two storms are alike [eg *Lanzerotti*, 1992]. Nevertheless it is useful to have some understanding of the chronology of a space weather superstorm (*Figure 7*).

First, there will be a general heightening of activity for some days ahead of the event as a large active region (or regions) rotates into view on the eastern side of the Sun. This period will be marked by frequent solar flares and CME launches as shown in the upper left of the figure. Most of these will be medium scale events: M-class solar flares and slow CMEs (speeds < 800 km s^{-1}) marked in amber. But a few events will approach extreme levels: X-class solar flares and fast CMEs (> 800 km s^{-1}, so likely to generate a bow shock). These are marked in red. Many of these flares will produce HF radio wave absorption across the sunlit side of the Earth - strong absorption in the case of X flares (so marked in red), but weaker for M flares (amber). At this stage, the fast CMEs are likely to miss the Earth, so an extreme geomagnetic storm is avoided. But some of the energetic

EXTREME GEOMAGNETIC STORM CONDITIONS ARE LIKELY TO CONTINUE FOR MANY HOURS AND PERHAPS DAYS particle particles from the CME shock will reach Earth, producing a heightened radiation environment (amber) and perhaps even extreme conditions (red). The heightened level of activity is likely to produce disturbances in the solar wind that in turn cause heightened geomagnetic activity at Earth (as shown by the amber bars on the right at t < 0). But this is only a precursor to the main event.

At t = -1.25 days (shown by the red bar) a very fast Earth-directed CME launches. This may be associated with an X-class solar flare and is very likely followed within 10 minutes by the onset of a severe radiation storm with the particle radiation being generated at the shock wave ahead of the fast CME. At t=0 the fast CME arrives at the Earth and generates an extreme geomagnetic storm (as shown by the red bars at the right for t > 0).

Extreme geomagnetic storm conditions are likely to continue for many hours and perhaps days (eg if multiple CMEs impact the Earth). The geomagnetic storm is not a period of continuous extreme activity. Instead, it comprises pulses of extreme conditions separated by periods of lower (but still high) activity – as shown by the interleaving of red and amber bars in the figure. These pulses, known as substorms, arise as energy from the CMEs is temporarily stored in the Earth's magnetic tail before being explosively released towards the Earth.

4.5 Probability of a superstorm

The key question, critical to placing this natural hazard in context with other natural hazards, is a good estimate of the probability of a superstorm on the scale of, or greater than, the Carrington event.

In the UK, for planning purposes a reasonable worst case superstorm with the strength of the Carrington event is currently considered to be a 1-in-100 year event. However, given that the longest geomagnetic data set extends back only ~170 years and satellite particle effects are at best measured over ~50 years, understanding of how often an event of this type will affect the Earth is poor.

The Sun is believed to produce several tens of Carrington-class CMEs every century but most miss the Earth or the IMF is oriented North. For example, on 23 July 2012 a Carrington-class coronal mass ejection was seen to leave the far side of the Sun [*NASA*, 2012] and reached NASA's STEREO-A spacecraft just 19 hours later. STEREO-A orbits at the same distance from the Sun as the Earth so this speed is comparable to that of the Carrington CME. Preliminary data from the spacecraft show a huge magnetic field (~100 nT) at first northward, but then turning southward. Energetic particles were in fact detected at Earth despite the poor connection to the event beyond the west limb of the Sun. If the event had occurred several days earlier very intense fluxes might have reached the Earth. The advent of satellite missions such as STEREO means that we are now likely to see many more of these events, and this is an opportunity to improve our assessment of their occurrence rate.

There are also reasons to anticipate events larger than those seen in recent history. Studies of long-term solar change [*Barnard et al.*, 2011] indicate that the Sun has been in an atypical state for the last 40 years. It has been suggested that the current gradual decline in the overall strength of the solar wind magnetic field will increase the Mach numbers of CME shocks and thus increase their ability to generate energetic particles [*Kahler*, 2009].

Various other authors are addressing this estimation problem in different ways. A paper looking at several parameters, including observed CME speeds and the strength of the equatorial current system in Earth's magnetosphere, concluded that the risk of a superstorm could be as high as 12% per decade [*Riley*, 2012]. This certainly provides a useful estimate but the reader should treat such estimates with considerable caution.

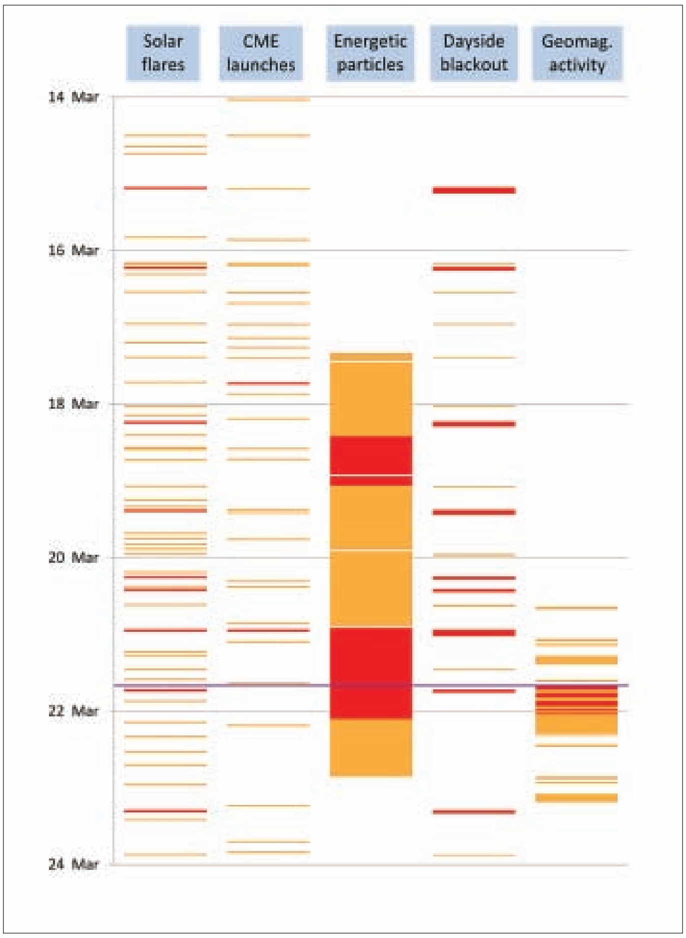


Figure 7: Indicative timeline of environmental phenomena leading up to an extreme space weather event with time advancing from top to bottom. The figure shows five key phenomena: solar flares (leftmost column), CME launches (left of centre), solar energetic particle fluxes (centre, dayside blackout (strong HF radio absorption on sunlit side of Earth) (right of centre) and geomagnetic activity (right hand column). Red indicates the occurrence of extreme conditions while amber indicates heightened activity somewhat below the extreme case (see text) © Rutherford Appleton Laboratory

The use of nitrates in ice cores as a possible proxy for solar energetic particle events [*McCracken et al.*, 2001] has recently been shown to be flawed [*Wolff et al.*, 2012]. However, *Miyake et al.* [2012] has shown that the study of carbon-14 in tree rings is possibly a good proxy for atmospheric radiation events over the last 3,000 years. The dominant natural source of carbon-14 is a result of the collision of neutrons (usually from galactic cosmic ray interactions in the atmosphere but with additional large spikes from solar energetic particle events) with nitrogen molecules at altitudes of 9 to 15 km. This study indicates that there was an intense atmospheric radiation event during the years 774-775 AD which was much more intense than any seen in the recent era of direct radiation measurements. [*Melott and Thomas.*, 2012] have shown that this event could have arisen from a solar energy release around 2×10^{26}J, around 20 times greater than the energy release from the Carrington event [*Clauer and Siscoe*, 2006]. We note, however, that there is no corroborative evidence that this event was associated with a severe geomagnetic storm - but that may just indicate that the associated CME missed the Earth or that records of bright aurora from this era were not preserved.

Maehara et al. [2012] has studied the flares on other stars using 120 days of data from the NASA Kepler mission. This mission is designed to study the light curves of large numbers of stars in order to look for dips that would indicate the passage of an exoplanet across the disc of its parent star. Serendipitously this mission is also ideal for looking for bright flares (energy $> 10^{26}$J) on those stars. The paper reports observations of 14 flares on 14,000 Sun-like stars (similar surface temperature and spectral type, slow-rotation periods >10 days). They use this to estimate that a flare of energy $> 10^{27}$J (again 10 and 100 times greater that from the Carrington event) will occur once every 800 years on a Sun-like star.

4.6 Solar superstorm environment – summary and recommendation

Summary

The recurrence statistics of an event with similar magnitude and impact to a Carrington event are poor, but improving. Various studies indicate that a recurrence period of 1-in- 100 to 200 years is reasonable and this report makes assessments of the engineering impact based on an event of this magnitude and return time. If further studies provide demonstrable proof that larger events do occur – perhaps on longer timescales - then a radical reassessment of the engineering impact will be needed. The headline figure of 100 years should not be a reason to ignore such risks. To demonstrate the issue, but without disturbing the main narrative of the report, a short outline of the implications of rare events is presented in Box 1.

The environmental specification for the superstorm may also be considered as a work in progress with the current estimates provided in *SEIEG* [2012].

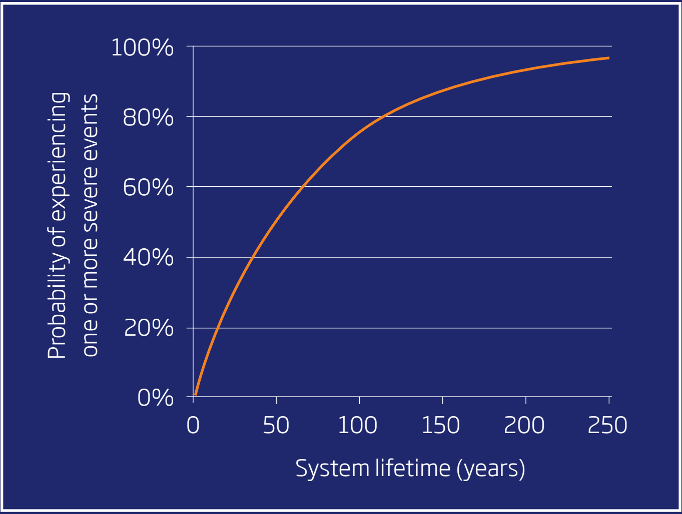
Recommendation

The UK should work with its international partners to further refine the environmental specification of extreme solar events and where possible should extend such studies to provide progressively better estimates of a reasonable worst case superstorm in time scales of longer than ~200 years.

Box 1. Probability of extreme space weather events – implications and consequences for mitigation of risks

Given the potential risk from severe space weather events, it is vital to assess the likelihood that such events will occur in the future and to understand the nature of the risk. As with many other natural hazards, we have no means of predicting the occurrence of specific events, but we can make statistical estimates of their rate of occurrence. Such statistical estimates are valuable as they enable policymakers to compare the different risks and prioritise the resources applied to mitigate these risks.

For severe space weather, the generally accepted benchmark for assessing risk is that our planet experiences a Carrington like event. A recent paper looking at several parameters, including observed CME speeds and the strength of the equatorial current system in Earth's magnetosphere, concluded that risk of such an event could be as high as 12% in a decade [Riley, 2012].



This corresponds to a return period or recurrence interval of 79 years – but, this does not mean that we should expect a severe event every 79 years. Instead we expect these events to occur randomly in time. The usual 95% confidence interval implies we might only wait two years for a superstorm, but we might wait 300 years. This is a consequence of the nature of randomness.

Random systems also have no memory. The potential for the next severe event does not increase as time passes since the last event; similarly that potential is not smaller in the years immediately following a severe event. This is exactly equivalent of tossing a coin: a run of heads in a row does not make it any more likely you will get a tail next time. Despite the fact that we have had 150 years since the last Carrington-strength event, the average waiting time until the next major storm remains 79 years. Random events have no concept of being overdue.

The bottom line is that any system sensitive to space weather has a finite probability of experiencing a severe space weather event. The figure above shows how, given a 12% risk per decade, the probability of experiencing a severe event increases with system lifetime. The probability asymptotically approaches 100% over periods of several centuries. But if we focus on the lower left of the figure, and take 10% as the acceptable level of risk, any system with a design lifetime of more than 8.25 years needs to consider the risk from severe space weather events similar to that first recorded by Carrington.

5. Impacts on the electrical power grid

5.1 Introduction

Rapid variations of the geomagnetic field on time scales of a few seconds to a few tens of minutes, caused by space weather, induce an electric field in the surface of the Earth. This electric field, in turn, induces electrical currents in the power grid and in other grounded conductors. These currents can cause power transmission network instabilities and transformer burn out. For example, severe space weather caused damage to two UK transformers during the 13 March 1989 storm [*Erinmez et al.*, 2002], the same storm that caused much disruption to the operation of the Hydro-Quebec grid [*Bolduc*, 2002].

The strength of the electric field (in volts per kilometre: V/km) depends on the relative resistance – or conductivity - of the sub-surface. In the UK typical electric field strengths are of order 0.1 V/km during quiet space weather, but may rise to ~5-10 V/km during severe space weather (for example during the October 2003 storm [*Thomson et al.*, 2005]. The electric field itself changes on a time scale similar to the driving geomagnetic variation.

The induced surface electric field can, under certain assumptions, be modelled as a collection of voltage sources in each of the conducting lines in the network. In principle, for a given conducting line, the larger the separation between grounding points the larger the geomagnetically induced currents (GIC) that will flow in the line. In practice, however, the GICs are determined by all the line and grounding resistances of the network and by the local resistance of the Earth itself. The modelling tools that are required here are essentially based on Ohm's and Kirchoff's laws from electrical engineering.

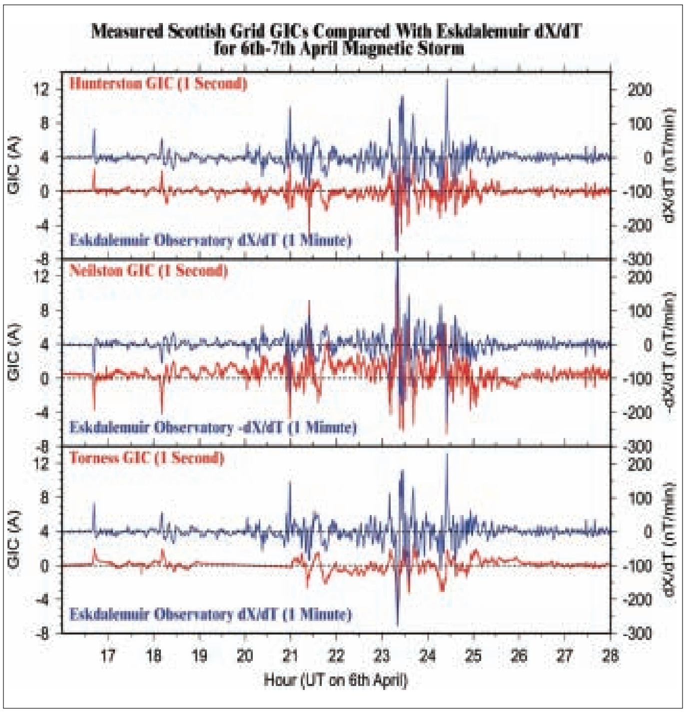


Figure 8: Time rate of change of the north (dX/dt) component of the geomagnetic field from the Eskdalemuir observatory in the UK, compared with simultaneously measured GIC data (Amps) at three sites in Scotland, during a moderate storm on April 2001, when no grid problems were reported. Horizontal tick marks are given every 30 minutes © British Geological Survey (NERC) and Scottish Power

Monitoring the rate of change of the horizontal component of the geomagnetic field is a simple but still good indicator of the strength of GIC in any grounded network [*Beamish et al.*, 2002], see *Figure 8.*

However the correlation between measured magnetic and GIC data falls off with separation between measurement sites, necessitating a network of magnetic monitoring sites across the country. In the UK, the NERC/BGS magnetic observatory network and the University of Lancaster SAMNET variometer array together provide such a network. In the UK horizontal magnetic field changes of around 500 nT/min or more have been known to be associated with high voltage grid problems over the past two to three decades [eg *Erinmez et al.*, 2002]. This is a useful rule-of-thumb threshold used in UK geomagnetic monitoring activities.

Figure 9 shows the modelled response of the UK high voltage (400 kV and 275 kV) electricity transmission system to the 656 nT/minute variation observed at the Eskdalemuir magnetic observatory at the peak of the Halloween storm of 2003 [*Beggan*, unpublished, 2012].

The induced geoelectric field varies at a frequency that is much less than the network's operating frequency of 50Hz. Thus, GICs appear as quasi direct currents superimposed on the system's alternating current. These quasi-DC currents magnetise the transformer core in one polarity and can cause the core to magnetically saturate on one half-cycle of the AC voltage. This half-cycle saturation causes peaks in the magnetising current drawn from the grid system.

The most serious effect of this half-cycle saturation is that when the core saturates, the main magnetic flux is no longer contained in the core. The flux can escape from the core and this can cause rapid heating in the transformer and the production of gases in the insulating oil, which leads to alarms being triggered, shut-down of the transformer, and, in the most severe incidents, serious thermal damage to the transformer. Even if no immediate damage is caused, the performance of the transformer can degrade, and increased failure rates over the following 12 months have been observed [*Gaunt and Coetzee*, 2007].

The more likely effect, although less serious, arises from voltage instability. Reactive power is required on the grid to maintain voltage. Under conditions of half-cycle saturation, transformers consume more reactive power than under normal conditions. If the increase in reactive power demand becomes too great a voltage collapse can occur leading to a local or, if severe enough, a national blackout.

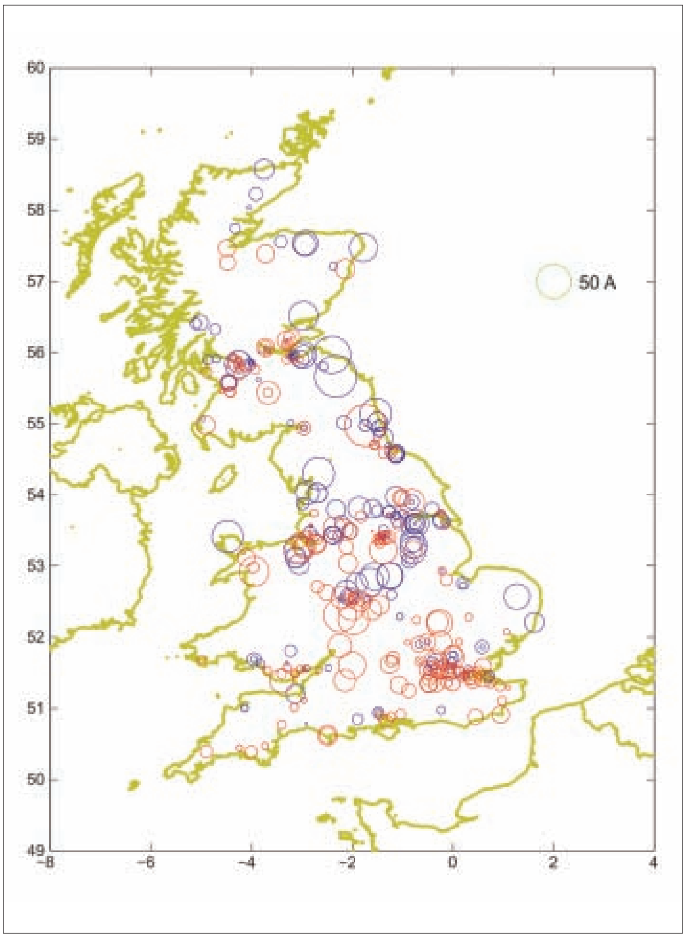


Figure 9: Simulation of GIC flow across a simplified model of the UK 400 and 275 kV transmission system at 21:21 UT on 30 October 2003. A reference 50 Amp spot size is also shown. Red and blue denote GIC flowing to/from the Earth at major transformer substation nodes

A third effect arises from the distortion of the magnetising current which becomes non-sinusoidal, and injects harmonics into the grid. Under normal operating conditions, these harmonics are indicators of faults such as negative phase sequences, and the presence of harmonics triggers protective relays. But under GIC conditions the relays can disable equipment, such as static variable compensators, designed to support the voltage on the system, making voltage collapse more likely. It was this triggering of relays that led to the blackouts in Quebec Province in 1989 and Malmö, Sweden in 2003. National Grid experienced distortion of the magnetising current effects on 14 July 1982, 13-14 March 1989, 19-20 October 1989 and 8 November 1991.

Some transformer designs are more at risk than others. In particular, single phase transformers, and three-phase transformers with five-limb core transformers are more at risk than three phase transformers with a three-limb core, because the quasi-DC flux induced by the GIC can flow directly in the core [*Price*, 2002].

5.2 Consequences of an extreme event on the UK grid

US space weather, transformer and modelling experts have recently produced conflicting reports analysing the impact on a large space weather event on the US system. In an influential report *Kappenman* [2010] suggests that a one-in-100-year event could lead to catastrophic system collapse in the US taking many years and trillions of dollars to restore. However, a comprehensive February 2012 report from the North American Electric Reliability Corporation [*NERC*, 2012], suggested that loss of reactive power and voltage instability would be the most likely outcomes. At a Federal GMD Technical Conference on 30 April 2012, it was clear that there was still more work required to agree a proportionate management of the risk. Ongoing work, prepared by National Grid on a severe space weather event for the UK, initially from June 2011, aligns more closely with the conclusions from the NERC paper.

Studies of an extreme event scenario in the UK have been based on a rate of change of the Earth's magnetic field of 5000nT/min [*NERC*, 2010], being approximately a one–in-100-year event (or even rarer) according to *Thomson et al.* [2011]. This compares with the March 1989 event where rates of change of the magnetic field in excess of 500nT/min were observed, during the largest geomagnetic disturbance experienced in the UK since the development of a national grid.

National Grid owns and maintains the high-voltage electricity transmission system in England and Wales, together with operating the system across Great Britain including Scotland. National Grid and Scottish transmission system owners have been aware of the effects of space weather for many years, particularly the effect of geomagnetically induced currents (GICs) on large supergrid transformers that, in England and Wales, step the voltage down from 400kV or 275kV to the 132kV distribution networks. [*Erinmez et al.*, 2002]. Transformers owned by generating companies that step up the voltage to connect to the high voltage grid are also known to be at risk, as has been shown from experience in the USA and South Africa.

Since the last peak of the solar cycle, the Great Britain transmission system has developed to become more meshed and more heavily loaded. It now has a greater dependence on reactive compensation equipment such as static variable compensators and mechanically switched capacitors for ensuring robust voltage control. Thus there is increased probability of severe geomagnetic storms affecting transmission equipment critical to robust operation of the system. The greatest effects of GICs are normally experienced at the periphery of the transmission systems, as in *Figure 9*.

UK studies that are still on-going, sponsored and undertaken by National Grid indicate that a Carrington-level event could have a significant impact. The current worst case estimates are for some local blackouts lasting a few hours as a result of increases in demand for local reactive power. National Grid has a well-established plan for this type of event, whether or not caused by space weather, and the plan is rehearsed regularly. It is estimated that, for a prolonged storm with maximum rate of change of the geomagnetic field of 5000 nT/min, around six grid transformers in England and Wales and a further seven grid transformers in Scotland could be damaged and taken out of service. This number of failures is within the capacity of National Grid's transformer spares carrying policy to replace sufficient transformers to restore demand. The time for an emergency transformer replacement, when a spare is available, would normally be 8 to 16 weeks although the record is four weeks. A significant delay can be the time required to get permission to transport the spare transformer on the road, and in the event of a severe event it is hoped that priority would be given to allow transport to occur more rapidly.

Most nodes have more than one transformer available and consequently most failures would not lead to prolonged disconnection events. However, National Grid's analysis is that on the order of two transformer substations in Great Britain could experience disconnection through transformer damage. If this occurred, it is likely it would be in remote regions where there is less transformer redundancy.

Generator step-up transformers are potentially at more risk than Super Grid network transformers because of their design (normally single phase or three phase with a five-limb core) and the fact they are operated close to their design loading. As a consequence, network transformers installed since 1997 have, wherever possible, been three phase with a three-limb core, the most GIC resistant type. Although some transformers at higher risk remain on the system, operational mitigation would reduce the possibility of damage.

Interconnectors to France, the Netherlands and to Northern Ireland are operated as High Voltage Direct Current (HVDC) links. As DC equipment, they are not susceptible to GIC effects. However, the power electronics that convert the current from DC to AC at each end of the interconnectors can be disrupted by the harmonic distortions on the AC side. This means that these links may not be available during a severe space weather event.

IT IS ESTIMATED THAT, FOR A PROLONGED STORM WITH MAXIMUM RATE OF CHANGE OF THE GEOMAGNETIC FIELD OF 5000 NT/MIN, AROUND SIX GRID TRANSFORMERS IN ENGLAND AND WALES AND A FURTHER SEVEN GRID TRANSFORMERS IN SCOTLAND COULD BE DAMAGED AND TAKEN OUT OF SERVICE.

5.3 Mitigation

There are three approaches to dealing with the risks posed by GMDs:

1. Understanding the risks through modelling.
2. Implementing appropriate engineering or hardware solutions, such as increasing the spares holding and installing GIC blocking devices.
3. Implementing forecasting and operational procedures, similar to those for other severe risk events such as terrestrial weather.

The solution adopted in the UK is a combination of all three. This is broadly similar to solutions adopted by other system operators.

Modelling, simulation and testing

Network models typically characterise each network as interconnected serial and parallel DC resistances, representing transformer and power lines, acted on by voltage or current sources determined from the modelled surface electric field. The relative simplicity of the methodology – though models of the UK 132 kV, 275kV and 400 kV system currently have over 600 transformer nodes and 1200 interconnecting lines – means that simulation of the grid response to hypothetical and historical events is feasible [*Thomson et al.*, 2005]. Moreover, the flexibility of such network models lends them to simulation of proposed grid modifications, particularly where additional long lines are being considered [*Turnbull*, 2011]. Scenario modelling reveals how the pattern of GIC hazard changes with any proposed reconfiguration and whether GICs are reduced or enhanced at known 'weak points'.

Models and simulations need testing against measured GIC data. Monitoring of GIC at all network grounding points is impractical, given the numbers of nodes and connections in the UK system. However, selection of appropriate monitoring points can be achieved with reference to previous model simulations. Edges and less-connected portions of the grid are typically places that experience larger GICs.

Detailed understanding of the effects of GIC on individual transformers at individual nodes in the system is still lacking. These effects include thermal damage, increased reactive power consumption and production of harmonics in the presence of GIC. For example, the oil in the transformer is degraded under repeated small GIC events and this can result in unexpected failures and greater vulnerability during a superstorm. A number of studies are underway in the UK and USA, but more remains to be done. Both theoretical modelling and, where feasible, the practical testing of transformers are needed.

Forecasting mitigation

National Grid is working with the British Geological Survey (BGS) to provide a real-time monitoring and warning system, known as MAGIC (Monitoring and Analysis of GIC). This system will build on the expertise that BGS has gained both through involvement in

the academic community researching the effect of solar storms, knowledge of the underlying geophysics of the British Isles and experience of previously providing a monitoring and warning system for Scottish Power.

Accurate forecasting of ground magnetic field variations that drive GIC, whether through detailed magneto-hydrodynamic (MHD) models of the magnetosphere, with solar wind input, or through simpler parameterised models, is currently limited. Detailed forecasts of whether the Great Britain grid will be affected and, if so, which parts of the grid in particular will be affected are, therefore, not possible. Parallel activities in North America, such as the Solar Shield project [*Pulkkinen et al.*, 2009] are progressing.

Undoubtedly, improved GIC forecasting capability is a key demand from industry. Hence the transition of one or more MHD-based models to operational readiness would be a major step forward in improving predictive capability. We note that NOAA SWPC and NASA/CCMC in the US are currently undergoing an evaluation of relevant models.

Engineering mitigation

Since 2003, National Grid has adopted transformer design standards that ensure a high level of GIC resilience. In practice this means that only three limb transformers are used in the network. An audit of all Supergrid transformers (SGTs) was completed in May 2011 and this is regularly updated to determine those transformers with a high vulnerability to GIC. The latest transformer audit includes generator transformers which, because of their design and their heavy loading, are more at risk than most SGTs. Grid Supply points (GSPs) have then been analysed using a simple GIC model (developed by BGS) to identify how many transformers at each nodal point are at-risk, and GSPs have been rated according to the proportion of at-risk transformers present. As a consequence, the target spares holding of SGTs has been reviewed and increased.

Consideration is being given to the installation of series capacitors on certain transmission lines. These can block the flow of GICs but can alter the electrical properties of the network in ways that must first be understood before deciding if such devices are suitable for the Great Britain network. Series capacitors are primarily being considered for reasons of load flow control.

More generally, National Grid is monitoring the development of neutral current blocking devices for transformers. These devices are as yet in their infancy, but consideration will be given to any promising developments, again with the proviso that their impact on the system would need to be addressed. Provision for such devices is being considered to protect transformers for new DC links.

National Grid will consider whether the sensitivity of protective relays to harmonics in the system is appropriate. This will rely on data gathered from other network operators where such disturbances are more common.

Consideration is also being given to the provision of transportable recovery transformers that could temporarily meet some of the demand needs at a node that had lost all its supergrid transformers through thermal damage. Such devices are still only at the prototype stage.

Operational mitigation

In the build-up to a significant space weather event, National Grid would take actions that are, in many respects, similar to those taken in the face of severe terrestrial weather. These actions would be triggered by National Grid's space weather monitoring team following on from advice from BGS, the Met Office and other forecasting bodies. National Grid would issue warnings and advice to customers and third parties, as specified by business procedures.

Increased reserves of both active and reactive power would be scheduled to reduce loading on individual transformers and to compensate for the increased reactive power consumption of transformers. Where possible, circuits would be returned from maintenance work, and other outage work postponed, increasing the stability of the system against voltage fluctuations. Substations would be run to maximize the connectivity of the grid where possible. Large power transfers between areas would be reduced, particularly on the Scottish-English transfer boundary.

National Grid would operate an 'all-in' policy where all of its transformers were switched in, reducing the individual neutral current through any one, and all generators would be instructed to generate, reducing the loading on generator transformers, and also increasing reserves.

Throughout the duration of a geomagnetic disturbance, control room engineers at the National Control Centre would monitor the state of the system using the MAGIC tool, assessing which assets are most at risk and identifying areas where voltage instability and reactive power demands are likely to be a problem.

To recover from either an intentional or non-intentional shutdown of part of the Grid or the whole Grid requires a procedure known as Black Start. National Grid has a well-rehearsed plan for Black Start, and generating machines are at all times scheduled to provide this Black Start capability.

5.4 National electricity grid – summary and recommendations

Summary

The reasonable worst case scenario, assumed to be of the order of a one-in-100-year event, will have a significant impact on the national electricity grid. Current estimates are for some local electricity interruptions lasting a few hours. In addition, around six super grid transformers (SGTs) in England and Wales and a further seven grid transformers in Scotland could be damaged and taken out of service.

Because most nodes have more than one transformer available, not all these failures would lead to a disconnection event. However, National Grid's analysis is that around two nodes in Great Britain could experience disconnection. This number of failures is within the capacity of National Grid's transformer spares carrying policy. The time for an emergency transformer replacement, when a spare is available, is normally eight to 16 weeks, with a record of four weeks. Some generator step-up transformers will be at more risk than SGTs because of their design. Lesser storms, compared to a one-in-100-year event, will have progressively less impact on the system

In the build-up to a significant space weather event, National Grid would take actions triggered by National Grid's space weather monitoring team following on from advice from the British Geological Survey, Met Office and other forecasting bodies. National Grid would issue warnings and advice to government, customers and third parties to enable them to mitigate the consequences.

Recommendations:

- The current National Grid mitigation strategy should be continued. This strategy combines appropriate forecasting, engineering and operational procedures. It should include increasing the reserves of both active and reactive power to reduce loading on individual transformers and to compensate for the increased reactive power consumption of transformers.
- There is a need to clarify and maintain a very rapid decision-making process in respect to an enhanced GIC risk.
- Consideration should be given to the provision of transportable recovery supergrid transformers and to GIC blocking devices, which are still in their infancy.
- Further geophysics, transmission network and transformer modelling research should be undertaken to understand the effects of GIC on individual transformers, including the thermal effects, reactive power effects, and the production of harmonics.
- Long-term support for geomagnetic and GIC monitoring should be maintained.
- The National Grid should better quantify the forecasting skill that it requires and assess this in the light of foreseeable improvements following from current and future scientific research.

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6. Other geomagnetically induced current effects

6.1 Pipelines and railway networks

GICs can be induced on any long lengths of earthed electrical conducting material during a solar storm.

Boteler [1977] and *Trichtchenko and Boteler* [2001] have discussed GICs in the context of pipelines, but reported effects in the UK are hard to find.

Evidence also exists of space weather impacting railway networks, with recent papers in the literature referring to Russian and Swedish networks [eg *Eroshenko et al.*, 2010; *Ptitsyna et al.*, 2008; *Wik et al.*, 2009]. However, again the study team was unable to assess whether this is an important issue for the UK.

6.2 Trans-oceanic communications cables

Optical fibre cables are the backbone of the global communications networks. They carry the vast majority (99%) of internet and telephone traffic and are much preferred to links via geosynchronous spacecraft since neither human voice communications nor the standard TCP/IP protocol can efficiently handle the ~0.3s delay imposed by the long paths to geostationary satellites. Optical fibres are more resilient to space weather than their twisted copper wire predecessor, which was very prone to GIC effects.

However, electric power is required to drive optical repeaters distributed along the transoceanic fibres and this is supplied by long conducting wires running alongside the fibre. These wires are vulnerable to GIC effects as was demonstrated during the geomagnetic storm of March 1989. The first transatlantic optical fibre cable, TAT-8, had started operations in the previous year and experienced potential changes as large as 700 volts [*Medford et al.*, 1989]. Fortunately the power system was robust enough to cope. Similar but smaller effects were also seen during the Bastille Day storm of July 2000 [*Lanzerotti et al.*, 2001]. We are not aware of any effects occurring during the Halloween event of 2003, but that event was relatively benign in terms of GIC effects.

6.3 Recommendations

- Government and industry should consider the potential for space weather damage on the optical fibre network through overvoltage on the repeaters and should consider whether appropriate assessment studies are necessary.
- UK railway operators and pipeline operators should be briefed on the space weather and GIC risk and should consider whether appropriate assessment studies are necessary.

ELECTRIC POWER IS REQUIRED TO DRIVE OPTICAL REPEATERS DISTRIBUTED ALONG THE TRANSOCEANIC FIBRES AND THIS IS SUPPLIED BY LONG CONDUCTING WIRES RUNNING ALONGSIDE THE FIBRE.

7. Radiation impacts on satellites

7.1 Introduction

A solar superstorm, such as that described in section 4, dramatically increases the fluxes of radiation particles seen by satellites, creating a number of hazards to their operation and longevity. The specific effects and impacts will depend upon satellite orbit, and design.

7.2 Electron effects

Electrons cause electrostatic charging and cumulative dose (ageing) effects on satellites. The Earth's dynamic outer electron belt (see section 5.4) is particularly troublesome for satellites in geostationary- and medium-Earth orbits (GEO and MEO) and has caused numerous anomalies and outages as a result of electrostatic build-up and discharge. Low Earth orbit satellites (LEOs) can also be subject to charging effects in auroral (high latitude) regions.

A discharge can readily couple into sensitive electronics causing data upsets, false commands and even component damage. There are two types of charging that can occur: surface-and internal-charging. Both involve complex interactions between the space environment, materials and microelectronic systems and they continue to prove difficult to analyse, model and mitigate.

- *Surface charging* is caused by low energy electrons (<100keV) which interact only with surface materials of the spacecraft. Under certain conditions, potential differences of many kilovolts can arise between various different surfaces, leading to an electrostatic discharge. Surface charging was first seen in the 1970s and 80s but techniques to suppress it, through the grounding of surfaces and the use of conductive coatings, were introduced. In recent years it has come back in new and subtle forms causing major power losses in solar arrays. Surface charge rises and recedes over quite short timescales (minutes).
- *Internal charging* is caused by high-energy electrons *(>100 keV)* which penetrate into the spacecraft equipment where they deposit charge inside insulating materials (especially plastics) and ungrounded metals. The phenomenon first came to light in the 1980s and is still a problem today. Discharges tend to occur very close to the sensitive and vulnerable components. Internal charging requires a day of two of persistently high fluxes to build up enough charge to be a threat, but this often occurs in magnetic storms.

Electrons also cause ionising dose damage to microelectronic devices through a build-up of trapped charge in insulating (usually silica) layers. Equipment power consumption goes up, noise immunity is reduced and decision thresholds may change. Ultimately complete failure of equipment may occur. Cumulative dose damage has rarely been a cause of satellite failure since it is relatively straightforward to analyse and large safety margins are used. This might not be so in the event of a solar superstorm.

7.3 Solar energetic particle effects

Energetic protons and ions are present as a background flux of galactic cosmic rays and can be greatly enhanced for several days at a time by solar energetic particles (SEPs). These add to total ionising dose (as discussed above) but also cause two further effects:

- *Displacement damage* disrupts the crystalline structure of materials used in microelectronic devices. These defects reduce the performance of transistors and are especially important for optoelectronic devices such as opto-couplers where current transfer ratios are reduced and for solar cells where efficiency is degraded
- *Single event effects (SEE)* arise from the charge depositions of individual particles in the sensitive regions of microelectronics. Such depositions occur via direct ionisation (dominant for the heavy ions) and nuclear interactions (dominant for protons and neutrons). Effects range from soft (correctable) errors to hard (permanent) errors, which can include burnout of some devices such as metal oxide semiconductors. With feature sizes reducing to tens of nanometres and critical charges reducing to femtoCoulombs these are a growing problem and a number of systems have been damaged or compromised. Further details of single event effects, which are also of growing importance in avionics (see section 11), can be found in the box below.

The high upset rates produced by SEPs are an increasing problem [*Dyer et al.*, 2004] and have been blamed for a number of

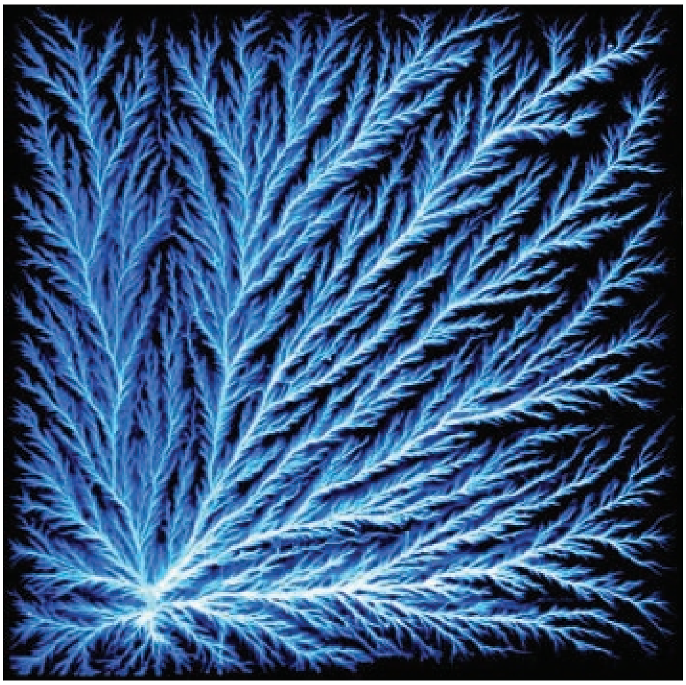

Figure 10: An electrostatic discharge caused by electron accumulation in an insulator: such discharges are a major cause of anomalies on satellites and have proved difficult to suppress © K A Ryden

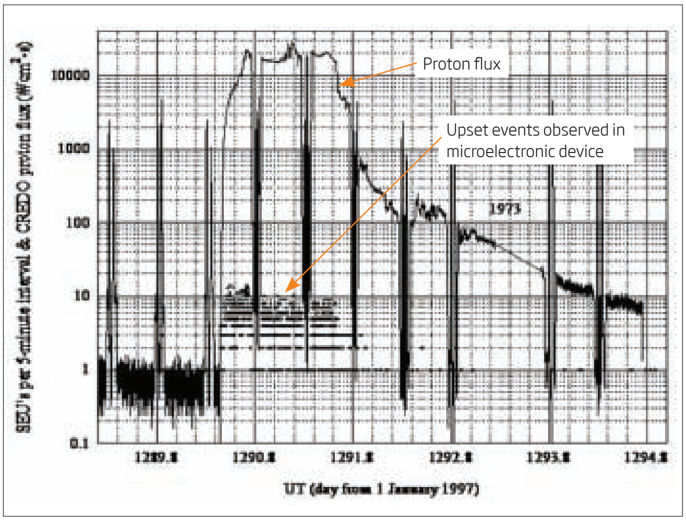

Figure 11: Observations of the onset of SEE on a satellite coincident with arrival of solar particles during Bastille Day event on 14 July 2000 – fluxes and SEE rates would be greater during an extreme event [Campbell et al., 2002]. Note that periodic dips and spikes in radiation are also observed since the observing satellite routinely crosses regions of radiation trapped by the Earth's magnetic field © QinetiQ

operational outages and failures. *Figure 11* shows observations of upsets in an analogue-to-digital converter during the Bastille Day solar particle event in July 2000. SEPs are more probable around solar maximum, although they can occur at any time in the solar cycle.

The University of Surrey's UoSAT-2 spacecraft, orbiting in a highly inclined, low Earth orbit (700km, 98°), happened to be in operation during the SEP event of October 1989. This spacecraft was one of the first to make use of commercial-off-the-shelf (COTS) components, and in particular carried large amounts of dynamic random-access memory (DRAM) that was very sensitive to single-event upsets (SEUs). It is thus a valuable source of data on the effects of such an event on radiation sensitive devices operating in space. During the event, there was an order of magnitude increase in SEU activity [*Underwood*, 1996] but it is worth noting that the automatic on-board error mitigation system (error-detection and correction coding plus memory 'washing') was able to cope without difficulty, and the spacecraft remained fully operational during this and indeed all the events encountered.

A subset of data from Giove-A, the UK-built satellite launched in preparation for the Galileo mission for the period 2006 [*Ryden et al.*, 2008] illustrates (*Figure 12*) the highly dynamic nature of the medium Earth orbit environment. Although not a solar maximum period, it shows the various consequences of a CME-driven solar storm which occurred in December 2006 with two associated SEP events (shown in red). Soon after the SEPs are seen, the measured internal charging threat (shown in black) due to energetic electrons increases considerably for over a week. (The internal charging threat is also enhanced, with a periodicity of the ~27 day solar rotation period being strongly linked to the presence of persistent coronal holes). While the electron fluxes are elevated, the measured total ionising dose (yellow and green lines) increases rapidly including in the aftermath of the December 2006 solar storm.

7.4 Satellite failures and outages

Unlike, for example, the UK electricity grid which is a single, well-defined system, there are around 1,000 satellites operating in different orbits and built to a wide variety of standards, specifications and engineering practices. Even satellites of the same nominal type usually contain different permutations of equipment and component fits. Some space weather interactions are probabilistic in nature (such as single event effects) and so even identical equipment may exhibit different responses.

Satellites are protected against space weather in a number of ways. Physical shielding is vital at component, equipment and spacecraft level to reduce particle fluxes and cumulative doses to acceptable levels. Circuits are designed to account for some degree of degradation and unwanted behaviour in microelectronic components and the components themselves are carefully selected, screened and tested. Data storage devices often employ some level of error detection and correction and important data values are checked for plausibility. At equipment level there is typically like-for-like redundancy to cope with single failures or, less frequently, a diversity of technology to avoid single mode failures. Design margins are used to account for uncertainty in the models and calculations used. Systems are also designed to limit the impact of faults and steer the system towards a safe state: operator intervention is then required to recover the system. In a serious case the satellite may go into a safe attitude position (eg Sun pointing) while awaiting operator recovery actions. In such cases a satellite service outage would occur but the vehicle should still be recoverable later on. In the meantime, services may have to be transferred to other satellites, either in-orbit spares (if available) or other satellites that have spare capacity.

CUMULATIVE DOSE DAMAGE HAS RARELY BEEN A CAUSE OF SATELLITE FAILURE SINCE IT IS RELATIVELY STRAIGHTFORWARD TO ANALYSE AND LARGE SAFETY MARGINS ARE USED. THIS MIGHT NOT BE SO IN THE EVENT OF A SOLAR SUPERSTORM.

Despite all these engineering measures, problems resulting from space weather have proven impossible to suppress altogether, even in normal conditions. While most such effects are noticeable only by the satellite operator, some do lead to service outages and, on very rare occasions, complete satellites failures. Key engineering reasons for these on-going problems include the following:

- introduction of new technology with unexpected sensitivities
- poor understanding of certain radiation interaction mechanisms
- inaccurate space environment models
- test facility limitations (ie we cannot fully replicate the space radiation environment on the ground)
- design or build errors which are ultimately exposed during a storm event
- storm intensity may exceed specified protection levels (specification level is a cost-risk balance).

Some significant public domain examples of satellite failures or outages which have been attributed to space weather are given in *Table 1*. These are based on data from satellites where data are relatively freely available, but it is likely that many problems encountered remain undisclosed due to commercial and security sensitivities. More than 47 satellites reported anomalies during the October 2003 CME-driven 'Halloween' storm period [*Satellite News Digest*, 2012] one scientific satellite was a total loss and 10 satellites suffered a loss of operational service for more than one day. In 2003, there were approximately 450 satellites in orbit

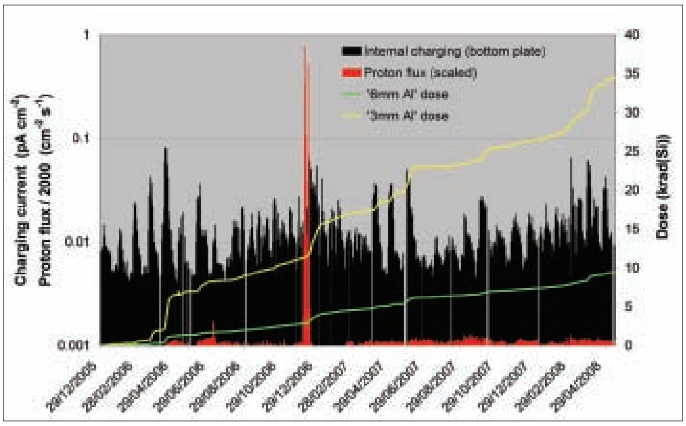

Figure 12: Measurement of space weather engineering hazards in medium Earth orbit on the Giove-A mission. The CME-driven storm in December 2006 produced two separate, sudden, increases in proton fluxes (marked in red) and then, after a couple of days, caused substantially increased rates of internal charging (black) due to acceleration of electrons in the outer belt. Energetic electron levels remained elevated well into January 2007. Ionising dose, which has an 'ageing' effect, was measured at two depths of aluminium shielding, 3mm (yellow line) and 6mm (green), both of which exhibited a rapid increase in the aftermath of the storm due to the presence of the energetic electrons. A similar sequence of events on larger scale would be expected from an extreme storm © QinetiQ

whereas that figure has now increased by more than a factor of two. Given a similar event today we may expect ~100 satellites to report anomalies and approximately 20 satellites to have a loss of service for more than one day.

7.5 Engineering consequences of an extreme event on satellites

Radiation

A similar sequence of events, albeit on a much larger scale, would be expected during an extreme storm. There would be:

- one or more SEP events over several days leading to an increase in SEE and a rapid increase in displacement damage dose which will be especially notable in optoelectronic components (including the solar cells used to power the satellite)
- a sharp increase in the energetic electron environment a day or two after the arrival of the CME. This would cause internal charging hazards for many days or even weeks, together with surface charging threats
- a rapid increase in the radiation damage accumulated on the satellite due primarily to the electron environment increases but also with a proton contribution.

During an extreme event the energetic electron environment in some orbits could be up to an order of magnitude more severe [*Shprits et al.*, 2011] than those typically used in specifications and it is thought that solar particle fluxes could be up to three or four times more intense. Memory upsets and other erroneous events may increase so much that they exceeded a threshold above which the inbuilt mitigation approaches (eg error detection and correction) are no longer effective. Under these circumstances, linear scaling of anomaly rates from previous storms might not provide an accurate picture. *Odenwald et al.* [2006] has estimated up to 10 anomalies for every satellite every day as an upper limit (but noting very large uncertainties) based on an assumed Carrington event. However typically only a small subset of anomalies have an impact on service provision.

As well as anomalies, a solar superstorm could have a major impact on satellite lifetimes. The reasonable worst case SEP is expected to produce (in one go) a >30MeV proton fluence of approximately 3×10^{10} cm^{-2} [*SEIEG*, 2012] which is close to a typical lifetime fluence specified for long-life geostationary or medium Earth orbit satellites [eg *Feynman et al.*, 1993]. Subjected to such a SEP event, a newly launched satellite would rapidly use up this element of its designed-in radiation tolerance, but should nevertheless survive. The satellite would then however be vulnerable to further SEPs, but we do not know when these would occur. After a superstorm, older satellites might be operating well outside their radiation design-life but, fortunately, long experience shows that most spacecraft have the potential to significantly exceed their nominal design lives because of the extremely conservative design approaches

Date	Event	Satellite	Orbit	Cause (probable)	Effects seen
8 March 1985		Anik D2	GEO	ESD	Outage
October 1989	CME-driven storm	TDRS-1	GEO	SEE	Outage
July 1991		ERS-1	LEO	SEE	Instrument failure
20 January 1994	Fast solar wind stream	Anik E1	GEO	ESD – note: all three satellites were of same basic design	Temporary outage (hours)
20 January 1994	Fast solar wind stream	Anik E2	GEO	ESD – note: all three satellites were of same basic design	6 months outage, partial loss
20 January 1994	Fast solar wind stream	Intelsat K	GEO	ESD – note: all three satellites were of same basic design	Temporary outage (hours)
11 January 1997	Fast solar wind stream	Telstar 401	GEO	ESD	Total loss
19 May 1998	Fast solar wind stream	Galaxy 4	GEO	ESD	Total loss
15 July 2000	CME-driven storm	Astro-D (ASCA)	LEO	Atmospheric drag	Total loss
6 Nov 2001	CME-driven storm	MAP	Interplanetary L2	SEE	Temporary outage
24 October 2003	CME-driven storm	ADEOS/MIDORI 2	LEO	ESD (solar array)	Total loss
26 October 2003	CME-driven storm	SMART-1	HEO	SEE	Engine switch-offs and star tracker noise
28 October 2003	CME-driven storm	DRTS/Kodama	GEO	ESD	Outage (2 weeks)
14 January 2005		Intelsat 804	GEO	ESD	Total loss
15 October 2006	Fast solar wind stream	Sicral 1	GEO	ESD	Outage (weeks)
5 April 2010	Fast solar wind stream	Galaxy 15	GEO	ESD	Outage (8 months)
13 March 2012	CME-driven storm	Spaceway 3	GEO	SEE?	Outage (hours)
7 March 2012	CME-driven storm	SkyTerra 1	GEO	SEE/ESD?	Outage (1 day)
22 March 2012	CME-driven storm	GOES15	GEO	ESD?	Outage (days)

Table 1: Selected significant satellite losses and outages in the public domain [e.g. Satellite News Digest, 2012] that have been attributed to space weather. Note however that diagnosis of one-off events is rarely conclusive and the evidence base is generally circumstantial. Overall, complete losses are extremely rare, with temporary outages being more commonly observed © Royal Academy of Engineering 2012

A SUPERSTORM WILL CAUSE EXPANSION OF THE EARTH'S ATMOSPHERE, CAUSING DRAG ON LEO SATELLITES; ORBITS WILL BE DISTURBED AND PREDICTIONS OF SATELLITE POSITIONS WILL BE DEGRADED.

© NASA

against cumulative dose effects. Therefore, while some very old satellites (eg those already in life extension) might have a short lifespan (eg months) after the storm, a tidal wave of failures would not be expected and most would carry on for several years, some even reaching close to their full lifetime. However, the planning of replacements would need to be actively accelerated which has the potential to cause bottlenecks in the supply chain.

Satellites in MEO, such as those providing navigation services, already experience much higher levels of radiation than those at GEO – and to some extent this means that they are well protected. The radiation environment could, however, be further increased during an extreme event [*Shprits et al.*, 2011]. GPS has now flown in MEO for 600 satellite years and its resilience to solar storms, such as we have already seen during the satellite era, is excellent. However, the superstorm performance of GPS – and the other satellite navigation satellites – is as yet unknown.

It may be noted that a small number of defence satellites (eg UK Skynet) are built to higher environmental specifications to protect against high altitude nuclear events (HANE). The additional hardening is likely to be beneficial in an extreme solar event, although satellite ageing will still occur.

Atmospheric drag

A superstorm will cause expansion of the Earth's atmosphere, causing drag on LEO satellites; orbits will be disturbed and predictions of satellite positions will be degraded. Satellite orbit data then needs to be re-acquired which may take some days to complete. In extreme cases, low altitude satellites may experience significant aerodynamic torques which overcome the vehicle's attitude control system capability leading to termination of the mission as happened to Astro-D (~450km altitude orbit) during the storm of 14-15 July 2000.

7.6 Mitigation

Engineering

Assessing the impact of a solar superstorm and mitigating it through good design requires an appropriate environmental model. For routine space weather a range of models is available and owners and manufacturers are free to choose which they use and how. Resilient satellites are already designed to have a high probability of operating through very disturbed environments. However, these environmental models are based on observations that do not include a superstorm and thus satellites are not explicitly specified for such an event, although extrapolations of the models can be of relevance. Widely used models include NASA AE8 and AP8 [*Vette*, 1991] for radiation belt electrons and protons respectively. These are currently being updated to version 9 but are not yet released [*NASA GSFC*, 2012]. It is not yet clear if these new models will be appropriate for superstorm conditions.

Increasing the level of hardening of critical satellites to withstand an extreme event should be possible, but the development and enforcement of improved engineering standards that embrace extreme environments will be required. The major space standards [eg European Cooperation of Space Standardisation (ECSS)] include environments that are at least close to the Carrington event (as presently understood), especially with respect to cumulative effects such as dose and damage. However current satellite specifications do not typically cover low probability extreme events and thus might be exceeded by up to an order of magnitude. Operators and owners of critical satellite systems vital to national security and economic wellbeing should be strongly encouraged to ensure that their satellites can operate through and beyond an extreme storm event.

Heavy reliance on a single satellite design presents a greater risk of loss of service. Contingency plans should include the possibility of switching to or benefitting from other independent satellite services. Multi-constellation GNSS receivers will be the norm within a few years, and these receivers treat the aggregation of satellites from multiple constellations as one large constellation. Thus the individual GNSS receivers will be inherently robust to a satellite service denial.

Forecasting

Satellites are generally intended to operate autonomously but in extreme events it is important to anticipate the impact of the event so that operations staff can be better prepared. Operations teams usually have to manage several satellites from one control centre with minimum staffing levels so advance warnings of storm events will be beneficial to increase alert levels and draw in extra staff. Certain space systems can be placed in safe mode if adequate warning is given, however, most satellites will need to operate through the extreme event.

SEPs, giving rise to SEEs, arrive at close to the speed of light. Events afflicting spacecraft usually take up to several hours to peak and then can last several days. Consequently, providing the satellite survives the initial blast of high-energy particles, a judgement regarding the longevity of the event may be made.

Warnings of potential spacecraft charging events may be achievable in the medium term since they are linked to the arrival of Earth-directed CMEs. However, while observations of CMEs can provide some measure of warning the associated geoeffectiveness is dependent on the polarity of the interplanetary magnetic field. Only once this has been determined can actionable advice be provided to the satellite operators and, unfortunately, this cannot be determined until the CME reaches the L1 position. By this time, the warning has reduced to an hour at most [*Horne*, 2012] and probably 15-30 minutes.

Testing

Testing of components for space radiation effects relies on major facilities: these are generally beyond financial capability of any one aerospace company and are under continual financial threat. Government support and international collaboration are imperative to ensure continued availability.

7.7 Satellites – summary and recommendations

Summary

During an extreme space weather event, some satellites may be exposed to environments in excess of typical specification levels. This would increase microelectronic upset and failure rates and also create electrostatic discharge hazards. In addition, significant cumulative radiation doses could be received causing rapid satellite ageing. Because of the multiplicity of satellite designs in use today, there is considerable uncertainty on the overall behaviour of the fleet but experience from more modest storms indicates that some disruption to satellite services must be anticipated. Fortunately the conservative nature of spacecraft designs and their diversity is expected to limit the scale of the problem.

During the superstorm, our best engineering estimate, based on the 2003 storm, is that around 10% of spacecraft will experience an anomaly leading to an outage of hours to days but most of these will be restored to normal operations in due course. It is unlikely that outages will be spread evenly across the fleet since some satellite designs and constellations will inevitably prove more vulnerable than others by virtue of their detailed design characteristics. A few spacecraft might be lost entirely during the storm through a sudden damage mechanism such as electrostatic discharge.

In the months after the extreme storm, old satellites such as those in life extension mode may start to fail as a result of the ageing (dose) effects (we note that as many as one in 10 satellites in geostationary orbit are thought to be in life-extension mode). Recently launched satellites would be expected to survive the event but with higher risk thereafter from incidence of further (more common) storm events. Consequently, after an extreme storm, all satellite owners and operators will need to carefully evaluate the need for replacement satellites to be launched earlier than planned in order to mitigate the risk of premature failures. Obviously such a scenario has potential for creating a bottleneck in the satellite supply chain which will raise questions of priority.

Recommendations:

- Extreme storm risks to space systems critical to social and economic cohesion of the country (which is likely to include navigation satellite systems) should be assessed in greater depth; and users of satellite services which need to operate through a superstorm should challenge their service providers to determine the level of survivability and to plan mitigation actions in case of satellite outages (eg network diversification).
- The ageing effects of an extreme storm across the whole satellite fleet should be modelled to determine if a serious bottleneck in satellite manufacture or launch capacity could be created.
- Research should be actively pursued to better define the extreme storm environments for satellites and consequential effects. Collaboration with the NASA *Living with a Star* programme would be highly beneficial.
- Observations of the space radiation environment and its effects should be maintained and developed. Such measurements enable post-event analysis of satellite problems, the development of improved physical models which can be used in satellite design phases and the development of better warning and forecasting.

Box 2: More detailed description of single event effects (SEEs)

A single event upset (SEU) is generated when the critical charge in a semiconductor is exceeded causing the memory cell to change logic state with an associated change in the memory data word. For complex systems with large amounts of memory, it is important that recovery time is short compared to the time between SEE, so that inbuilt redundancy is adequate. During a large solar event, the time between individual SEE will be much shorter than it is in the nominal atmospheric radiation environment.

Multiple bit upset (MBU) occurs when the energy deposited in the silicon of an electronic component by a single ionising particle causes upset to more than one bit in the same word. These errors are mainly associated with memory devices, although any register is a potential target. Many memory manufacturers minimise the risk of MBU in modern memories by arranging the individual bits in a word non-contiguously. Because more than one bit in a single word are affected in the same event MBU can avoid detection through simple parity checks.

Multiple cell upset (MCU) occurs when the energy deposited in the silicon of an electronic component by a single ionising particle induces several bits in an integrated circuit (IC) to upset at one time. These errors are mainly associated with memory devices, although any register is a potential target. The occurrence of MCU is increasing as device feature size (and therefore the space between transistors gets smaller).

Single event burnout (SEB) takes place in high voltage electronic devices, where despite their comparatively large feature size they are also at risk of SEE and burn out from atmospheric radiation.

Single event transient (SET) is a class of non-destructive soft-error that can cause changes of logical state in combinational logic, or may be propagated in sequential logic, through 'glitches' on clock or set/ reset lines, etc. To date, this has not been a significant threat, as device behaviour has been dominated by errors in registers and memory cells – ie SEUs. However, as devices are further scaled down to smaller feature sizes and faster speeds, SETs, are expected to become more probable. In contrast to SEUs, which do not show clock frequency dependence, SETs depend significantly on the operating speed of the devices in question – slower devices are less vulnerable.

Single event functional interrupt (SEFI) is observed as an unexpected loss of functionality, or otherwise unexpected change of state of a device due to a particle strike in the internal state-machines of a device. Early reports were confined to microprocessor SEFIs, however, new generation data handling devices, such as advanced memories and field-programmable gate arrays (FPGAs), have also been found to be susceptible. Functionality is usually restored by power-cycling the device (soft SEFI) – but sometimes permanent damage is done (hard SEFI).

Single event gate rupture (SEGR) is caused when a heavy-ion passing through an insulator under high field conditions leads to the catastrophic breakdown of the insulator with a consequent thermal runaway condition. Such events may occur in the gate dielectric of non-volatile static random access memory (SRAM) or electrically-erasable programmable-read-only memory (EEPROM) during a write or clear operation. The increasing use of such technology in data handling systems means that SEGR is an increasing risk factor in COTS systems.

A single event latchup (SEL) will persist until power is removed from the device. Single event latchup can be avoided at component level by choosing devices that are not susceptible to SEL. Integrated circuit manufacturers can reduce the risk of SEL using fabrication techniques such as substrates that include controlled epitaxial layers and silicon on insulator technology.

8. Ionising radiation impacts on aircraft passengers and crew

8.1 Introduction

High-energy cosmic rays and solar particles incident on the Earth spawn a multitude of other high-energy particles through nuclear interactions in the upper atmosphere. These high-energy particles generate secondary particles that reach a maximum flux at about 18 km and are then progressively attenuated by the atmosphere so that only the most penetrating component can be measured on the ground. Typically, at aircraft cruising altitudes the flux of ionising radiation is ~ 300 times higher than at sea level and consequently these particles can have an impact on aircraft passengers and crew because of the increased exposure to ionising radiation.

It is well established that ionising radiation can be injurious to human health. The harm caused can be divided into stochastic effects, which are probabilistic in nature, and tissue reactions which are deterministic in nature. Tissue reactions have a threshold for induction whereas stochastic effects do not. Two quantities are defined to determine the incidence of these effects.

- The absorbed dose, which is a measure of the energy deposited per unit mass of tissue in the form of ionisation and excitation (the unit 1 gray or Gy = 1 J kg^{-1}). Tissue reactions are only encountered for energy deposition greater than 0.5 Gy [*ICRP*, 2012] which is typically only relevant in accident and emergency situations. Tissue reactions are caused by cell damage or killing, and the effects are seen within days, sometimes with fatal consequences. A solar superstorm comparable to the Carrington event would be far too small to cause tissue reactions for altitudes up to 18 km, so they will not be discussed further. However, this might be a problem for astronauts who could receive much higher doses.
- The effective dose, which is the absorbed dose weighted for the radiosensitivity of each organ and the type/energy of radiation. The effective dose is measured in sieverts (Sv) and the probability of cancer and hereditary effects is believed to correlate linearly with the effective dose, with 1 Sv corresponding to a 5.5% increase in lifetime risk of fatal cancer. Aside from severe accident and emergency situations, these are the risks to human health that are generally of concern.

The field of radiation protection is overseen by the International Commission on Radiological Protection (ICRP), which produces periodic recommendations on all aspects of the field [*ICRP*, 1991; 2007]. The recommendations of the ICRP are invoked as EC Basic Safety standards [*Council of the European Union*, 1996] which are then followed into UK legislation as the Ionising Radiations Regulations published by the Health and Safety Executive [*Health and Safety Executive*, 1999]. Following the 2007 recommendations of the ICRP there has not yet been a revision of the EC Basic Safety Standards, but the IAEA has published international basic safety standards [*IAEA*, 2011].

The ICRP divides radiation exposures into occupational, medical and public, with different recommendations applying to each category of exposure. Also, in terms of optimisation, ICRP, divides exposure situations into "planned", "existing" and "emergency" [*ICRP*, 2007]. These apply to both occupational and public exposures with the annual dose limit for occupational exposures set to 20 mSv and that for public exposures set to 1 mSv. The 1996 EC Basic Safety Standards and 2011 International Basic Safety Standards explicitly include exposures of air crew as occupational exposure, but air travel is not considered for either business or leisure travel. Pregnant air crew are restricted to 1 mSv per declared period of pregnancy. FAA guidelines limit exposure in pregnancy to no more than 0.5 mSv in a month.

Long haul crew typically receive an occupational dose of 4 to 6 mSv per year [*Lindborg et al.*, 2004.] with 6 mSv being specified as an action level in Article 42 of EU Directive 96/29 Euratom that was adopted in the UK on 13 May 1996 and enacted in an amendment to the Air Navigation Order. For comparison, the UK average natural background dose rate at sea level is 2.2 mSv per year (from rocks, radon, internal sources and cosmic rays) [*Watson et al.*, 2005] while medical diagnostic doses range from 0.014 mSv for a chest X-ray, to 6 mSv for computerised tomography of the chest [*Wall et al.*, 2011] and higher for other interventions [*Fazel et al.*, 2009]. The average medical exposure in the UK is 0.4 mSv per year [*Watson et al.*, 2005].

Under normal conditions, the geomagnetic field confines the radiation effects from solar energetic particles to high latitude paths, but this includes flights on some of the busiest routes, such as those from UK to North America and Japan. There have only been a few measurements of solar particle enhancements on board commercial flights and these have mostly come from the now retired Concorde which was compelled to carry a monitor [*Dyer et al.*, 1990]. Recent observations have also been made in April 2001 and October 2003 [*Getley et al.*, 2005; *Getley et al.*, 2010]. These observations have enabled calculations to be made for other events and flight routes. For example, during the major event on 23 February 1956, it has been calculated that there was a 300-fold increase (over background) at high latitudes and 12km altitude, with corresponding dose rates for contemporary aircraft and flight paths of several mSv hr^{-1}. This could have caused some air crews to exceed the current annual occupational flight limits in just one flight [*Dyer et al.*, 2007]. Fortunately, such large events are rare and it is estimated that since 1942 only six events would have resulted in a dose in excess of 1 mSv on a flight from London to the west coast of the USA [*Lantos and Fuller*, 2003]. More recently, on 20 January 2005, a major event caused a factor 50 increase in the Antarctic region corresponding to effective dose rates of ~ 3 mSv hr^{-1} at cruising altitudes [*Dyer et al.*, 2007]; [*Butikofer et al.*, 2008]. Fortunately for aviation, this was very short-lived and localised such that the northern hemisphere rates were an order of magnitude lower.

The International Civil Aviation Organisation has recognised the potential issues of space weather and has commenced activities to provide operational requirements, guidance and the potential for space weather information services [*ICAO*, 2010].

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8.2 Consequences of an extreme event

If the geomagnetic field is highly disturbed when the particles arrive, then much lower latitudes may be exposed with significant exposure down to the tropics.

At conventional cruising altitudes (33,000 to 39,000 feet), a superstorm could result in a radiation dose to aircrew and passengers of greater than 20 mSv. This is greatly in excess (by a factor 20) of the annual dose limit for a planned exposure to the general public and comparable or in excess of the annual occupational dose limit of 20 mSv for workers. However, a dose of 20 mSv implies an increased lifetime cancer risk of only 1 in 1,000 for each person exposed which should be considered in the context of a lifetime cancer risk of about 30% [*ONS*, 2012].

Radiation emergencies are essentially dealt with by consideration of individual risk. Conventional nuclear emergencies and accidents have led to either very large exposures of individuals or had the potential for very large exposures. They are characterised by the possibility of taking mitigating action and thereby reducing the risks from significant exposure of individual workers or members of the public. The potential for significant individual risks resulting from radiation exposure on commercial flights seems small, although this must be qualified by acknowledging the uncertainty in the maximum dose rates that could result at aviation altitudes.

If a major solar storm took place, then a large number of members of public and air crew could be exposed. During 2011, UK aircraft operators uplifted 111,082,766 passengers, which corresponds to an average of ~304,000 passengers a day. We assume that this is a global event and experienced on both the day and night sides of the Earth. This is somewhat pessimistic, but we will optimistically assume that in the event of a solar superstorm the aircraft can land or reduce altitude within one hour. Given these assumptions ~13,000 passengers (on UK carriers alone) could be exposed to ~20 mSv. This would result in widespread public concern and an urgent need for advice and reassurance on the doses received. .

While it is tempting to compare a solar superstorm with other radiation emergencies in terms of collective dose, it is more relevant to compare with domestic radon exposure; radon is also background radiation and the action level is set according to individual risk. In the UK, the action level for which remedial measures in homes are advised, is set to 200 Bq m^{-3}, which corresponds to an annual effective dose of about 10 mSv y^{-1} [*McColl and Prosser*, 2001]. The target level for UK homes is half this value, but it still equates to about 5 mSv y^{-1}. This latter dose rate is about a quarter of the estimated dose received by passengers during a solar superstorm, and it represents an ongoing exposure rather than a one-off dose.

8.3 Mitigation

Pre-event planning

The impact on passengers and aircrew of an extreme solar storm might need to be considered as an emergency situation, where reference levels define doses or dose rates above which actions to reduce exposure are necessary. These reference levels would need to be applied based on pre-event considerations of the risk from exposure, the effectiveness of remedial measures and the consequences of those remedial measures. The ICRP does not specify values for emergency reference levels but sets bounds of 20 mSv to 100 mSv; hence the lower limit of concern for emergencies coincides with the estimates of individual doses from a Carrington scale event. Emergency plans tend to be drawn up on the basis of probability and impact, with a probability threshold estimate of 10^{-5} per annum being used. It is not clear how probable a solar superstorm would be, but a per annum risk between 10^{-2} and 10^{-3} would seem reasonable.

In its 2007 recommendations, the ICRP defined radiation emergencies as: "*situations that may occur during the operation of a planned situation, or from a malicious act, or from any other unexpected situation and require urgent action in order to avoid or reduce undesirable consequences.*" In its follow-up to those recommendations, it stated that "*The Commission recommends that plans should be prepared for all types of emergency exposure situation: nuclear accidents (occurring within the country and abroad), transport accidents, accidents involving sources from industry and hospitals, malicious uses of radioactive materials, and other events, such as a potential satellite crash*" [*ICRP*, 2009]. These statements do not specifically include or exclude an event such as a solar superstorm.

In its document on the application of the 2007 recommendations of the ICRP, the HPA stated that "*emergency situations are likely to be characterised by one or more of the following: significant uncertainty concerning current and future exposures, rapidly changing rates of potential exposure, potentially very high exposures (ie those with the potential to cause severe deterministic injury), and loss of control of the source of exposure or release.*" [*HPA*, 2009]. While the potential to cause deterministic injuries (tissue reactions) at commercial aviation altitudes is small, a solar superstorm would conform with the other characteristics. Taken together with the ICRP definitions, there is a case for considering a solar superstorm as a radiation emergency. It is possible that doses to a specific organ or tissue, such as the lens of the eye, could require consideration, though this is more likely to have occupational implications rather than emergency ones. The definitions of what constitutes an emergency are based on individual risk rather than collective dose, and the individual risk associated with a solar superstorm is likely to be low.

Aspects of a solar superstorm that mitigate against its consideration as a radiation emergency are its short duration and the lack of scope for taking action to reduce doses. If real time monitoring of dose rates improves, either in terms of the available satellite data or through on-board monitors, then it may become possible to take considered actions to reduce doses during a solar storm. Currently, however, the data available may not be processed until after event is finished; which could limit the radiation protection response to advice on the doses received.

When a Carrington-scale event, or even a storm as large as that from 1956, next occurs, there will be many members of the public in the air who will be exposed to additional radiation. It will be important to ensure that accurate information is provided to the people affected through all channels after the event. For example, advice will be needed on the levels of exposure experienced, the need for any medical checks (very unlikely), the advisability of further flights in respect of additional exposure and also any further work-related exposure. Special advice for pregnant women may be required.

Emergency plans are in place for conventional nuclear emergencies, with a view to covering all reasonably probable extreme events. There is therefore a case for the development of a specific emergency plan for public exposures from a solar superstorm, so that ad hoc decisions would not have to be made during the event. Such a plan would enable quick decisions to be made on the options available for reducing exposure: for example, reduction in altitude, rerouting and remaining grounded. These all have adverse consequences that need to be balanced against the radiation dose savings that can be made. The main requirement may be the provision of accurate and prompt information to the public. If there is another Carrington-scale event, members of the public who have flown will seek reassurance about health risks, especially if travelling while pregnant or with children. Those who have booked to fly will expect information on the risks for a significant period after the event.

Forecasting

Solar energetic particles from the solar superstorm arrive at close to the speed of light and prediction is essentially impossible unless solar precursors can be identified. The conditions on the Sun that produce spectra with large amounts of high-energy particles are currently not well understood. Near-term solutions based on such warnings are unlikely, but there is hope that in the medium to long term an approach based on precursors will provide the necessary skill to provide actionable advice.

Real-time monitoring

Ground level monitors are diminishing in number and this limits their ability to provide adequate directional and spectral information. Moreover, by the time a warning can be fed to aircraft its benefit is reduced because the maximum dose rates are reached in a matter of ten minutes or so.

Satellite-based warning systems can also be employed, but current satellite detectors use low energy particle thresholds that are more relevant to spacecraft operations than aircraft. This can result in numerous false alarms as well as missing other events. Even so, a sensible first step is to provide an alert service relaying information about current atmospheric radiation conditions to aviation authorities, airlines, pilots and other parties as part of normal meteorological reports: mitigating action could then be taken (eg to delay take-off) in line with the operating procedures of each affected body. These would preferably use a threshold of 300 MeV rather than those currently employed by the National Oceanic and Atmospheric Administration (NOAA) (> 10 MeV, >50 MeV and >100 MeV).

On-board, real-time monitoring is the only practical way to rapidly detect raised radiation levels that would allow action to be taken to mitigate the effects of particles from a solar superstorm. A height reduction can bring great benefit, eg a 30% reduction per 1 km of altitude, but unilateral and uncoordinated height reductions are highly risky and probably more risky than staying at altitude. An appropriate warning level at a rate that would exceed ~1 mSv in one flight - similar to danger levels for SEEs in avionics - is probably appropriate but this will require study.

Concorde was compelled to carry a radiation warning monitor [*Joint Aviation Authorities*, 2001] as are all commercial aircraft operating above 49,000 feet. A similar requirement has not been extended to other aircraft despite the fact that subsonic routes at high latitude are more exposed than Concorde because of the higher latitude effect and longer flight durations outweighing the influence of the reduced altitude [*Dyer et al.*, 2007]. Consequently, the avionic infrastructure to implement this mitigation approach is not in place and the cost might be a disincentive. However, it must be noted that the current situation of individual airline response to false positive NOAA warnings can result in wasted fuel and flight delay costs that could be avoided if reliable in-flight measurements were available. It should also be noted that many pilots would like information on the radiation levels to be immediately available to them so that they can make informed decisions. For example, the European Cockpit Association, which represents 38,000 commercial pilots, has written to the European Commission recommending that a visible warning should be provided.

Post event analysis and management of public concern

Post-event analysis will inevitably be needed to reassure the public. Crude estimates of the dose may be made using ground level and space monitors but the accuracy is limited by the lack of data, to factors between two and ten. In this context there is no substitute for onboard monitors.

8.4 Passenger and crew safety – summary and recommendations

Summary

Passengers and crew airborne at the time of an extreme event would be exposed to an additional dose of radiation estimated to be up to 20 mSv, which is significantly in excess of the 1 mSv annual limit for members of the public from a planned exposure and is comparable to about three CT scans of the chest. Such levels imply an increased cancer risk of 1 in 1,000 for each person exposed, but this should be considered in the context of a lifetime risk of fatal cancer which is about 30%.

No practical method of forecasting is likely in the short term since the high-energy particles of greatest concern arrive at close to the speed of light. Mitigation and post-event analysis is needed through better onboard aircraft monitoring. An event of this type will generate considerable public concern.

Recommendations

- Consideration should be given to classifying solar superstorms as radiation emergencies in the context of air passengers and crew. If such a classification is considered appropriate an emergency plan should be put in place to cover such events. While the opportunities for dose reduction may be limited, appropriate reference levels should be considered and set, if appropriate.
- Atmospheric radiation alerts should be provided to the aviation industry and concepts of operation should be developed to define subsequent actions based on risk assessment (eg delaying take-offs until radiation levels have reduced).
- Consideration should be given to requiring aircraft operating above a specified altitude (25,000-35,000 feet) to carry a radiation sensor and data logger. This would enable post-event analysis to allay public concerns and to manage any health risks.
- Consideration should be given to the sensor being visible to the pilot and to the development of a concept of operations whereby the pilot requests a reduction in altitude (noting that modest reductions can be beneficial) under solar storm conditions.
- Post-event information and advice on the radiation doses received should be available to passengers and crew (especially to pregnant women).

9. Ionising radiation impacts on avionics and ground systems

9.1 Introduction

Background galactic cosmic rays give rise, through collisions in the upper atmosphere to a cascade of secondary particles. These include neutrons, protons, electrons and muons with the flux of secondary particles much stronger at aircraft cruising altitudes than on the ground.

SEPs associated with solar storms also generate secondary particles in the upper atmosphere with the most energetic generating a ground level signature. When large increases in the flux of secondary neutrons are seen on the ground this is known as a ground level event (GLE). SEPs arrive within minutes of the optical flare signature since they travel at a significant fraction of the velocity of light.

These high-energy neutrons and protons are problematic because they interact with semiconductor material – on the ground or on board aircraft – where they give rise to lower energy protons, nuclear recoils and other secondary charged particles. These deposit a small amount of electronic charge causing single event effects (SEE), a generic term previously described in Box 2. With early generation large geometry devices, this electronic charge was small compared with the critical charge required to affect the device. However, increased integration with corresponding smaller geometry devices has brought with it an increased vulnerability to charge deposition.

The largest GLE on record (since measurements began in 1942) occurred on 23 February 1956. This GLE exhibited a 50-fold increase in neutron flux over the background for a few hours. It has been calculated that this event would have produced a 300 fold increase at 12 km compared with background conditions for this altitude [*Dyer et al.*, 2003]. Unfortunately, there is currently no good estimate of the flux corresponding to a Carrington superstorm and this obviously hinders our impact assessments. Our best estimate is that the environmental threat for a Carrington level superstorm is four times larger than the 1956 event, corresponding to a 200 fold ground level increase and a 1200 fold increase at 12 km.

9.2 Engineering consequences on avionics of an extreme event

Since the early 1990s there have been a number of open literature recorded instances of SEE in avionics at background levels of radiation [e.g. *Normand*, 2001; *Normand et al.*, 1997; *Olsen et al.*, 1993]. Increases in high-energy particles above this background, associated with a superstorm are then of concern because they increase the probability of an SEE in aircraft systems.

Normand [2001] illustrates the importance of SEE in the context of the background cosmic ray flux. He reported that upsets in an autopilot correlated with cosmic ray fluxes (as a function of latitude variation), and the average autopilot upset rate of one for every 200 flight hours was consistent with predictions based on ground irradiation of the same static random access memory chip (SRAM) [*Sims et al.*, 1994]. If these rates are scaled by calculated fluxes for the February 1956 event, upsets could have occurred more than once an hour for the particular autopilot under consideration if the system had reset after each upset [*Dyer et al.*, 2003].

In their final report [*ATSB*, 2011] on an incident near northwest Australia, the Australian Transportation Safety Bureau eliminated all environmental causes other than SEEs for false signals generated by an Air Data Inertial Reference Unit. In their lessons for new systems, they state "SEEs are a potential hazard to aircraft systems that contain high-density integrated circuits. Designers should consider the risk of SEE and include specific features in the system design to mitigate the effects of such events, especially in systems with a potentially significant influence on flight safety".

A superstorm would be likely to cause an atmospheric radiation storm lasting 12 hours or even more. It would be widespread, possibly extending down to the tropics if there were also a geomagnetic storm in progress. Consequently, all flight routes from the UK could be affected. As with spacecraft, the wide variety of avionic system designs makes a blanket assessment difficult, but during a storm period the most likely effects would be increased workload for pilots and air traffic controllers in order to handle aircraft systems failures.

9.3 Engineering consequences of an extreme event on ground systems

The atmosphere provides considerable protection to ground level systems and for this reason this study focuses on airborne systems. Yet we know that SEEs are occasionally seen on ground systems [*Normand*, 1996; *Ziegler et al.*, 1996] and are likely to be of increasing concern in the design of automotive electronics, miniaturised devices and safety-critical systems in general. Medical devices such as implantable cardiac defibrillators have been shown to give errors from cosmic rays [*Bradley and Normand*, 1998]. Upsets in major computing facilities correlate with altitude and, since a major server suffered significant outages and caused economic losses, certain server technologies have been tested in neutron radiation facilities [*Lyons*, 2000]. In light of this evidence, safety-critical ground systems such as those in nuclear power stations should consider the impact of superstorm radiation at ground level within its electronic system reliability - and safety-assessments. In the case of nuclear power a Carrington event may not be a sufficient case since relevant timescales for risk assessment may be as long as 10,000 years.

9.4 Mitigation

Avionics

Avionics are some of the most sophisticated but safe technological systems in common use. Avionics routinely incorporate redundant and majority voting systems to mitigate hazards – including the effects of solar storms (ground based safety critical systems also embody similar approaches making them also architecturally resilient to space weather). Notwithstanding these design approaches, specific engineering steps could be required to minimise the risk from SEPs.

Since 2006, a series of atmospheric radiation standards has been developed by the International Electrotechnical Commission (IEC) [*Edwards et al.*, 2004]. These are IEC 62396-1 Ed1, 2012 [*IEC*, 2012c] ; IEC 62396-2, 2012 [*IEC*, 2012a]; IEC TS 62396-3, 2008 [*IEC*, 2008c]; IEC TS 62396-4, 2008 [*IEC*, 2008b] and IEC TS 62396-5 [*IEC*, 2008a]. The IEC publications have the form of recommendations for international use, and are accepted by IEC national committees

Second or third party accreditation through the International Electrotechnical Commission Quality (Assessment System for Electronic Components) (IECQ) to the IEC technical specification, IEC/TS 62239-1 Ed.1, [*IEC*, 2012b] for electronic *component management* is increasing within the aviation industry. The specification contains a requirement (clause 4.3.7) that component level atmospheric radiation effects shall be assessed and documented in accordance with IEC 62396-1 Ed.1, 2012 section 9. This specifies quiet-time and moderate events (nominal environment). Solar storms are also mentioned in section 5.6 of IEC 62396-1 Ed.1, 2012 where there is a specification of the SEE rates which could be experienced during a superstorm event.

The IEC standard on avionics atmospheric radiation (IEC 62396-1 Ed.1, 2012 section 9) provides a methodology for documenting compliance of avionics which will be operated within an atmospheric radiation environment. This standard recommends that once the initial design is complete, all SEE sensitive electronic components should be identified and their atmospheric radiation susceptibility determined. Guidance for obtaining this information is contained within technical specification IEC 62396-2, 2012. If the component level SEE cannot be mitigated within the equipment design the standard recommends that the SEE be mitigated at the equipment or systems level. If this is not feasible, the part or equipment design might need to be changed.

For aircraft systems (as opposed to components) radiation standards and industry awareness are less developed. This is progressing through the revision of the SAE/EUROCAE Aerospace Recommended Practices, ARP 4761, which is exploring how to introduce consideration of SEE to the system safety assessment process.

The impact on equipment and systems of extreme events might be determined by irradiating the equipment in a wide area neutron radiation beam with the appropriate energy, spectrum and fluence, as described in technical specification IEC62396-2:2012. Levels comparable to an extreme event such as the Carrington Event at aircraft altitude would be required for such a determination. For avionics there are currently only two or three facilities worldwide that could generate radiation levels representative of the atmospheric environment. This situation should improve in the next two years with the opening of a dedicated beam-line (ChipIR) ISIS Spallation Neutron Source at the Rutherford and Appleton Laboratory in the UK. The ChipIR wide beam facility will enable complete powered and monitored equipment and systems to be irradiated at radiation levels equivalent or greater than a Carrington event to verify equipment SEE tolerance. However, to make this worthwhile, international aircraft industry cooperation will likely be necessary to agree on standardisation of test methodology and equipment design techniques to determine the most effective means of addressing this phenomenon.

Operational mitigation

As already described in the context of air passenger safety considerable reductions in superstorm radiation can be obtained by reductions in flight altitude (30% per km of altitude reduction) and possibly rerouting aircraft to lower latitudes. However, uncoordinated altitude reduction introduces risk. Even coordinated height reduction carries its own risk by increasing aircraft fuel burn which results in an aircraft possibly needing to re-route. A risk-benefit analysis would be required to evaluate this option.

Situational awareness of superstorm radiation – suggesting actions ranging from fastening seatbelts (to mitigate against any unexpected changes in height and direction introduced through the avionics) to altitude reductions or rerouting – can be provided to the pilot from ground, space and on board sensors. The latter is likely to be preferable from a technical standpoint because the measurement will be made where the risk occurs.

SEPs exhibit a wide spectrum of energies and it is currently impossible to forecast the spectrum – and danger – of the particles. Moreover, the first particles arrive within a few minutes of seeing the associated solar flare. Consequently, no practical forecast of the event, nor its associated impact can currently be provided.

9.5 Avionics and ground systems – summary and recommendations

Summary

Very little documentary evidence could be obtained regarding the impact of solar energetic particles on ground infrastructure and it is consequently difficult to extrapolate to a solar superstorm.

More documentary evidence of normal and storm time impacts is available in respect to avionics - no doubt because the operating environment has a higher flux of high-energy particles. Our estimate is that during a solar superstorm the avionic risk will be ~1,200 times higher than the quiescent background risk level. We note that the more critical avionics, such as engine control, are designed to mitigate functional failure at component, equipment and system level and consequently they will be partially robust to solar energetic particles.

Solar energetic particles exhibit a wide range of energies and it is currently impossible to forecast the spectrum of particles that might erupt from the Sun. Moreover, because the first particles arrive within a few minutes of the associated solar flare no practical forecast of an event and its consequences can currently be provided.

Recommendations:

- Ground-and space-derived radiation alerts should be provided to aviation authorities and operators. The responsible aviation authorities and the aviation industry should work together to determine if onboard monitoring could be considered a benefit in flight. Related concepts of operation should be developed to define subsequent actions, eg fastening of seatbelts or reducing altitude if the storm occurs on route or, if still on the ground, delaying take-offs until radiation levels have reduced. This could even include reductions in altitude if deemed beneficial and cost-effective.
- The responsible Aviation Authorities and the aviation industry should work towards requiring that future aircraft systems are sufficiently robust to superstorm solar energetic particles, including through the appropriate standards in atmospheric radiation mitigation – for example *IEC 62396-1* Ed.1:2012).
- Since the impact of a solar superstorm on ground-based systems cannot be clarified, further consideration is required. Systems with very high safety and reliability requirements (eg in the nuclear power industry) may need to take account of superstorm ground-level radiation on microelectronic devices within the system.

10. Impacts on GPS, Galileo and other GNSS positioning, navigation and timing (PNT) systems

10.1 Introduction

Transmissions from Global Navigation Satellite Systems (GNSS), including the Global Positioning System (GPS), GLONASS and Galileo, provide positioning and navigation services. The car satnav is perhaps the best known exemple, but ship and aircraft navigation, tracking of products and deliveries and emergency service dispatch are all increasingly dependent on the GNSS position and navigation services. GNSS also provides very accurate (tens of nanoseconds) timing services. Some telecommunications services use timing signals from GPS satellites to synchronise networks to facilitate data flow and the financial services industry uses GNSS to time-stamp transactions in high speed trading.

Ionospheric space weather affects GNSS transmissions in a number of ways and there are a number of compensatory approaches [*Cannon*, 2009; *Hernández-Pajares et al.*, 2011; *Kaplan*, 2005; *Mannucci et al.*, 1999; *Walter et al.*, 2000].

Coincident with the optical signature of the solar flare, solar radio bursts (SRBs), lasting for a few minutes to a few tens of minutes, may be detected at GNSS frequencies. During particularly active periods, and especially associated with a superstorm, there may be a number of bursts over the course of several days. SRBs can cause loss of lock in GNSS receivers [*Cerruti et al.*, 2006; *Cerruti et al.*, 2008] located in the sunlit hemisphere, due to an increase in radio noise interference. The effect of a SRB on GNSS was first seen on 5 December 2006, notably at solar minimum. This SRB was measured at 1 million solar flux units (one solar flux unit = $10^{-22}Wm^{-2}Hz^{-1}$) with smaller events on 6, 13 and 14 December that year. There was sufficient energy at GPS frequencies to interfere with receiver operation for 10 to 20 minutes on each occasion. Position data from several semi-codeless (and therefore not robust) receivers in the International GNSS Service (IGS) network were lost [*Carrano et al.*, 2009].

Arriving some 12-24 hours behind these prompt effects are the plasma particles associated with the CME. The latter indirectly cause perturbations to the ionospheric electron density over large portions of the globe and cause large-scale (10-1000km) wave-like structures and gradients in the ionosphere. Small-scale structures (less than 1km) are also generated and these cause scintillation (ie rapid changes in amplitude and phase) of the signals. Scintillation is not often observed over the UK and normally occurs at equatorial and high latitudes, where it is a serious and limiting problem. During an extreme space weather event, it is likely that ionospheric scintillation will be observed at UK latitudes and indeed globally.

OUR WORKING ASSUMPTION IS COMPLETE LOSS OF SERVICE FOR A PERIOD OF ONE DAY, HOWEVER, IT IS QUITE POSSIBLE THAT THERE WILL BE PERIODS WHEN AT LEAST ONE SATELLITE SIGNAL CAN BE RECEIVED AND TIMING SYNCHRONISATION REGAINED.

Amplitude scintillation, that causes rapid changes in the carrier-to-noise ratio, can lead to loss of carrier tracking in all receivers.

Phase scintillation that sufficiently disturbs the carrier phase causes the receiver phase tracking loop to lose lock impacting the reception of the important navigation data message which includes the satellite empherides. The code tracking loop, that measures range to the satellite, is fairly robust to phase scintillation and usually remains locked.

Loss of phase lock in receivers used in high integrity applications (eg aviation) is particularly important as these receivers need to regularly read the satellite data message. To mitigate this, satellite based augmentation systems (SBAS), such as WAAS and EGNOS, employ a message symbol rate of 500 symbols s^{-1}, together with a rate one-half encoder and repeated messages to deal with burst errors.

Unfortunately, our estimates of the disruption to GNSS caused by scintillation resulting from a superstorm are poor. Our working assumption is complete loss of service for a period of one day, however, it is quite possible that there will be periods when at least one satellite signal can be received and timing synchronisation regained. For critical infrastructure, our working assumption is extended to loss of service for a period of three days and includes an allowance for re-initialisation of the satellite constellation (or augmentation system) after the storm.

10.2 GNSS for navigation

Single frequency civilian navigation systems.
All GNSS systems have the option of operating in a single frequency mode and are dependent on a compensating model of the signal delay due to the electron density in the ionosphere. On average, the model compensates for ~50% of the ionospheric delay.

At the start (and end) of an extreme event when the ionosphere is highly disturbed, the position and navigation solution from a single frequency GNSS receiver will be significantly degraded due to a large mismatch between the actual ionosphere and the average model assumed by the receiver. Moreover, during these periods it is likely that, due to scintillation, not all satellites will be tracked and there will be a consequential dilution of precision. Single frequency

GPS is specified to provide horizontal errors below approximately 40 m for around 99% of the time. Typically, GPS errors are below 5 m. At the start and end of an extreme space weather event errors might be measured in 100s of metres.

During the main phase of the event, very significant electron density perturbations will occur and it is likely that scintillation will occur on all satellite paths. During this period, it is likely that positional and navigational solutions will be completely lost.

Dual frequency civilian navigation system.

GPS is being enhanced with a second open (civil) signal at the current L2 frequency (1227 MHz) and a new L5 frequency (1176 MHz). These frequencies will become fully operational over the next few years. Galileo will also add to the number of signals available for civil operations.

Dual frequency operation obviates the need for an ionospheric model and receivers equipped for dual frequency operation will be able to maintain accurate operation even in the event of significant electron density perturbations and gradients. However, the dual frequency receivers do not mitigate scintillation which will in fact be more prevalent at the lower frequencies. This means that during the start and end phases of a storm, there will be significant dilution of precision and during the main phase of the event position and navigation solutions will likely be lost. During a superstorm the best that can be expected is a marginal improvement over single frequency operation.

Augmented navigation systems and other differential systems

The preceding space weather vulnerabilities also apply to augmented navigation systems such as those designed for aircraft navigation and landing. These include the US Wide Area Augmentation System (WAAS) and the European Geostationary Navigation Overlay Service (EGNOS).

During the large geomagnetic storms in October 2003, vertical navigation guidance was unavailable from WAAS for approximately 30 hours [*FAA*, 2004]. It should be noted that WAAS horizontal navigation guidance remained continuously available and the integrity of the system was not lost. SRBs also affect the WAAS availability. The December 2006 SRB (the largest on record) caused a WAAS loss of vertical guidance for 15 minutes. As with the 2003 storms, operational integrity was maintained.

In an extreme event, the system metrics will be impaired at the start and end phases and service loss is likely during the main phase. Augmented and differential systems are particularly sensitive to medium scale spatial gradients in the ionosphere which will be prevalent during a solar superstorm. Furthermore, augmented systems (currently) use a type of receiver at their reference stations that tracks the phase of the military encrypted GPS signals. These semi-codeless tracking receivers require significantly higher signal-to-noise ratios than normal code and carrier tracking. This results in the receivers being extremely sensitive to phase scintillation on the L2 signal caused by a disturbed ionosphere. Under superstorm conditions, spatial gradients and tracking loss are likely to combine to cause a break in service of precision approach and other high integrity operations. Under these circumstances, SBAS is likely to support the reversionary non-precision approach (vertical navigation based on baro-altimetry).

10.3 GNSS for time and timing

Background

Many industrial applications require time or timing with appropriate accuracy, stability and reliability in order to operate effectively – or at all.

- Constant digital traffic flow across a telecommunications network requires accurate timing to ensure uninterrupted traffic throughput.
- The next generation of mobile data communications (dealt with in Chapter 12) will require accurate time slot alignment – now referred to in the ITU standards as time/phase.
- National power generation and distribution requires accurate time and time/phase.
- Server clocks need to keep the same time of day across the world, for example to support billing systems and financial trading.

Synchronising these time and timing applications to a common (UTC traceable) clock was made easier with the emergence of the GPS system.

National or core telecom network traffic timing

The UK national telecom networks first derived time from GPS in 1996, but with mitigation techniques to ensure complete loss of GPS did not compromise network timing.

Curry [2010] has explored the issue of holdover in networks when GPS is denied. This analysis has demonstrated that networks, and particularly critical national infrastructure networks, must be provisioned with rubidium or better (eg caesium) oscillators to meet the requirement for three day holdover in the event of a superstorm.

Most UK wireline *core* telecom networks, for both fixed line and mobile backhaul, now use GPS timing backed up locally by rubidium oscillators. In the event of GPS denial, the network timing is referenced to caesium atomic oscillators meeting the ITU G.811 standard – the current UK national network infrastructure, therefore, has the requisite holdover oscillators already in place. However, as more edge networks (as opposed to core networks), higher data rate packet-based networks and enterprise networks are deployed it is important that space weather vulnerability is regularly assessed.

GNSS for time/phase applications

Time/phase is the alignment of elements in a network to a common time base and most usually this is UTC which is easily derived from GPS. Typical examples of this requirement are energy networks which use it for synchrophasor operations and future smart grid applications. Time/phase is also needed in the time division duplex (TDD) variants of the 4G mobile networks. These are dealt with in Chapter 12.

GNSS for time-of-day applications

Some computer systems require traceable and accurate time-of-day in order to timestamp financial transactions, provide billing information, measure an event time and duration or log an alarm. While network time protocol (NTP) servers exist on the internet, these are sometimes not secure or accurate enough for mission – or commercially-critical applications. Consequently, some organisations implement their own NTP servers. These locally deployed NTP servers usually use GNSS as the source of UTC and back this up with high-grade oven-controlled crystal oscillators or rubidium oscillators. Loss of GPS would result in the NTP master clock progressively becoming less accurate and so the vulnerability is application dependent.

We can identify vulnerabilities according to applications that require clock accuracies of 1s, 1ms and 1μs. Analysis by *Curry* [2010] shows that an extreme space weather event will only have a severe impact on time-of-day applications where accuracies of better than a microsecond are required over the projected three days outage period. Emerging applications needing accuracy better than a microsecond include time stamping of high frequency trading in the financial services sector and smart grid applications.

If UTC alignment across multiple locations cannot be maintained against the temporary loss of GNSS, then other appropriate mitigation solutions might be considered. These include using network time and timing from the core (such as PTP) or other (than GNSS) off air sources of UTC-traceable time synchronisation such as eLoran signals. These are broadcast from Anthorn in the UK and are transmitted at 100 kHz and consequently also have (different) space weather vulnerabilities.

10.4 GNSS - summary and recommendations

Summary

GNSS positioning, navigation and timing are ubiquitous to our lives and important in a number of safety of life applications; and their unmitigated loss resulting from a superstorm would have severe social and economic repercussions.

Assuming that the satellites – or enough of them – survive the impact of high energy particles, we anticipate that a solar superstorm will render GNSS partially or completely inoperable for between one and three days. The outage period will be dependent on the service requirements. For critical timing infrastructure, it is important that holdover oscillators be deployed capable of maintaining the requisite performance for these periods. UK networked communications appear to meet this requirement.

With current forecast skills, it is inevitable that aircraft will be flying and ships will be in transit when the superstorm initiated. Aircraft use differential and augmented systems for navigation and in the future possibly for landing. With these applications set to increase, the potential for significant impact from an extreme space weather event will likewise increase. Fortunately, the aviation industry is highly safety conscious and standard operating procedures appropriate to other emergency situations are likely to provide sufficient mitigation to an extreme space weather event. These include other terrestrially based navigation systems. The challenge will be to maintain those strategies over the long term as GNSS become further bedded into operations.

This study has not explored the impact on ship navigation, but recognises that precision and non-precision navigation by GNSS is widespread and standard operating procedures will be needed to educate sailors on how to recognise a solar superstorm and deal with it in the possible absence of HF and satellite communications.

Recommendations

- All critical infrastructure and safety critical systems that require accurate GNSS derived time and or timing should be specified to operate with holdover technology for up to three days.
- Care should be taken to ensure that this requirement extends to cabled and fibre communications systems.
- Backup position, navigation and time services such as eLoran service (which in the UK is broadcast from the Anthorn transmitter) should be considered as an alternative to GNSS for UTC traceable time, timing and location based services. We note that the USA has set-up the Alternate Position Navigation and Time (APNT) programme that is working to reconfigure existing and planned ground navigation aids (e.g. Distance Measuring Equipment) and the ground based transmitters associated with automatic surveillance) so that they can back up GNSS well into the future.
- Since loss of GNSS would have a major impact on lives in general, and on shipping and air travel specifically, warnings of events should be provided through a nationally recognised procedure, possibly involving government crisis management arrangements, NATS, the CAA and the General Lighthouse Authority. Criteria should be established for the re-initiation of flying when it is safe to do so.

11. Impacts on radio communication systems

11.1 Introduction

Space weather events can affect the operation of radio systems in a number of ways. The effects may be prompt (ie they occur soon after the initial event on the sun) or delayed (ie some days later).

The following sections briefly outline the possible impacts on:

- terrestrial mobile communications networks
- HF communications and international broadcasting
- mobile satellite communications
- satellite and terrestrial broadcasting.

11.2 Terrestrial mobile communication networks

Systems considered in this section include:

- 2G public mobile communication systems, mainly based on the 3GPP GSM specification in the UK (mainly voice and data)
- 3G public mobile communication systems, mainly based on the 3GPP UMTS and HSPA specifications in the UK (higher rate data)
- 4G public mobile systems, expected to be based mainly on the 3GPP LTE and LTE-Advanced specifications in the UK, and to a lesser degree the IEEE 802.16 "WiMAX" technologies (even higher rate data)
- analogue private mobile radio, as used for a variety of business and security services, which are based in the main on FM technology according to a variety of proprietary and standardised approaches
- digital private mobile radio, as used by the emergency services, based on the ETSI TETRA specification.

Short-range systems such as Wi-Fi and Bluetooth are not considered. These are unlikely to be affected as they are typically used indoors and are less relied upon for critical services, although their use is proliferating.

Disturbance mechanisms

Terrestrial mobile systems typically work in the frequency range of 380 MHz – 3.5 GHz. Potential mechanisms for disturbance of mobile networks by an extreme space weather event are illustrated in *Figure 13*. They include:

- GNSS, if it is used for timing/synchronisation/location purposes at the base station or elsewhere within the network
- uplink access link (ie a mobile station transmitting to a base station)
- downlink access link (ie a base station transmitting to a mobile station)
- wireless backhaul (point-to-point and point-to-multipoint links between base stations and the mobile core network).

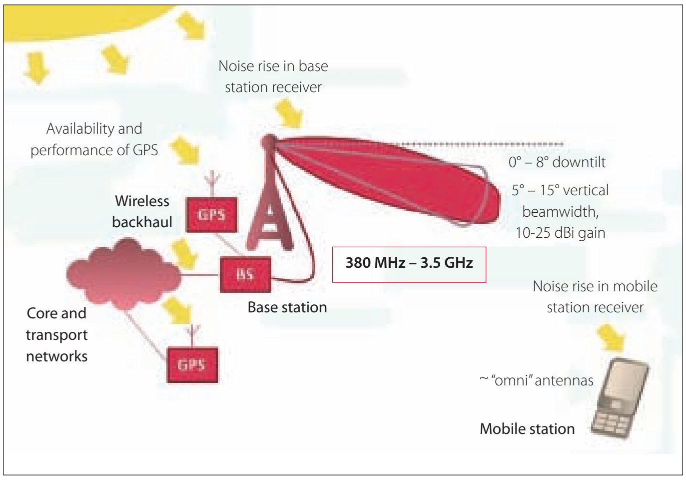


Figure 13: Potential mechanisms for disturbance of terrestrial mobile communications systems due to extreme space weather events
© Real Wireless Ltd

GNSS is potentially vulnerable to both solar radio noise bursts and also to ionospheric disturbances. Uplink, downlink and backhaul links are wholly terrestrial and are thus are only vulnerable to increased solar noise.

GNSS in mobile systems

The use of GNSS (currently GPS) at base stations varies significantly according to the wireless technology employed. The 3G CDMA base stations used by some operators in the US, Eastern Europe and the Far East, conform to the 3GPP2 standard use GPS for timing and synchronisation at each base station. By contrast, the 3GPP-based systems which are used for almost all public mobile systems in the UK were specifically designed not to require GPS support, by avoiding the need for synchronous operation between adjacent base stations. Consequently, UK public mobile systems should be largely unaffected by GNSS disruption during a superstorm.

One potential exception in 3GPP systems is synchronisation of base stations for the TDD variant of LTE technology (TD-LTE). GPS has been proposed to provide uplink/downlink synchronisation. However, this is an optional approach and could and should be avoided for critical systems via the use of network-based synchronisation techniques, such as via Precision Time Protocol (PTP) based on the IEEE-1588 standard which is currently being deployed. LTE in its FDD variant has just started to be deployed commercially in the UK. Wider deployments are expected following Ofcom's spectrum auction starting in early 2013. Although deployment of TD-LTE is likely to lag the FDD variant, it is important that the UK maintains the robust architectures currently being deployed where the application of the systems is critical.

Another potential exception where GPS may be used in 3GPP networks is in femtocells – miniature cellular access points used to enhance services in homes or small businesses. In the US, operators have used GPS to meet FCC requirements for emergency call location in femtocells. This has not been required by Ofcom in the

UK and other means of locating femtocells have instead been used to meet the relevant requirements [*Small Cell Forum*, 2012].

The TETRA system used by Airwave to provide communications to the emergency services in the UK does use GPS at each base station for timing and synchronisation (and possibly for operational location purposes also). The loss of GPS at TETRA base stations would, therefore, in the absence of mitigating techniques, lead to a loss of service. Furthermore, given the reliance of the emergency services on TETRA, the impact of a loss of service could be severe. Consequently, Airwave has mitigated against such potential impacts in several ways:

- by network configuration to allow base stations to continue to operate for an extended period of time in the absence of GPS. In our view, holdover for up to three days may be required
- via the provision of external power supply arrangements (battery and generator as applicable) to allow for non-mains running periods of up to seven days for the main part of the network
- the use of network-derived synchronisation techniques with references which are independent of GNSS

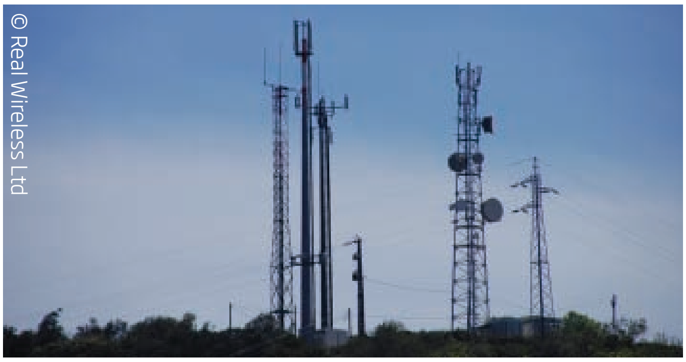
Existing contracts with Airwave are due to expire in the next few years, starting in 2016. It is strongly recommended that the specification of any replacement service should include appropriate mitigation to maintain and if appropriate extend resilience against loss of GPS over a period of three days.

The above assessment concerns the impact of GPS as deployed at base stations. It is possible that some mobile networks may make use of GPS elsewhere within the network: no such instance is known of or specified in relevant standards, but the possibility remains.

Radio noise in mobile systems

It has been reported [*Kintner et al.*, 2009] that solar radio bursts (SRBs) can affect the performance of mobile phone networks by increasing the noise in the system. The impact of such a noise rise will depend on the technical characteristics of the system, the intensity of the SRB and whether the antenna is pointed at the Sun.

Both base stations and mobiles are designed via various mechanisms to cope with signal outages of up to several seconds without loss of connection and only temporary loss of service. These mechanisms are likely to handle large noise rises with essentially the same robustness; consequently only longer duration events are likely to affect the mobile network. Furthermore, the external solar noise rise would have to be significant compared to the internal system noise.



Mobile handsets typically exhibit internal noise figures between seven and 10 dB in bandwidths of 200 kHz to 20 MHz and they have essentially omnidirectional antennas (except in specialised cases) with a gain of between around -5 dBi and +2 dBi. They are typically protected from solar noise by surrounding buildings and trees which block the line of sight to the Sun. Consequently, even if the external noise from the SRB is significant it will affect only particular mobiles rather than the whole system.

The impact of radio noise on base stations is more likely to be significant. Base stations have a lower noise figure (between 3-8 dB in the same bandwidth) than mobiles and, therefore, lower power SRBs will show a measureable impact. However, the base stations have relatively high gain antennae (10-20 dBi) with a narrow vertical beamwidth, (around 10°). They are typically placed in elevated locations and are usually directed downwards below the horizon with a little spill over at small angles above the horizon. Consequently, the base station will only be affected when the Sun is close to the horizon. Furthermore, the horizontal beamwidth is limited, typically to 80°-110° (base stations typically have multiple sectors to provide coverage at all azimuths) so only sectors facing the Sun will be affected. In conclusion, the SRB must occur close to sunrise or sunset and only those mobiles served by the sector in the direction of the Sun will be affected. Mobiles near the cell edge (ie those producing a weak signal at the base station) will be most affected. Wireless backhaul links could in principle also be affected by similar radio noise rise effects; however, they typically use narrow beamwidths thus reducing the probability that the Sun is in the beam during an SRB.

As a numerical example, we assume that at least one sector of every base station is directed at the horizon and hence could view the sun at near-maximum gain. Calculations (based on 900 MHz) then suggest that the base station noise rise will be (the noise rise of a mobile is given in brackets):

- noticeable [ie +1 dB] when solar flux density is above around 250 (12000) SFU and
- significant [ie +3dB] when solar flux density is above around 1000 (47000) SFU

There were 2,882 SRB events measured with more than 1,000 SFU (assuming a 12 minute window) during the period 1960-99, [*Bala et al.*, 2002]; ie more than one per week on average. However, no impacts on mobile phone networks have been reported, even during the most intense SRB on record in December 2006. However, it is possible that the effects are hard to discern among the many other variabilities in service quality on mobile networks and the overall impact is difficult to judge.

In an attempt to understand the impact of SRBs associated with a superstorm it is useful to look at the work of *Kintner* [2009] who defines intense SRBs as those in excess of 150,000 SFU. Such events, evaluated on the same basis, would correspond to around 22 dB of noise rise in base stations, and a corresponding severe loss of service. There have been several such events between the 1960s and 2006, although the precise number and characteristics are uncertain because of inconsistencies in various measurements. A fuller characterisation of the probability and impact of such events requires a better understanding of the expected distribution of extreme events by radio frequency, duration, intensity and temporal structure within an event (milliseconds to seconds).

In conclusion, extreme event SRBs are likely to have a widespread and noticeable impact on the mobile phone network, but only for base stations facing the Sun at dawn and dusk. The local time of the radio burst will therefore be critical and very different impacts will seen in different geographical locations.

11.3 HF communications and international broadcasting

Introduction

High frequency (3-30 MHz) point-to-point communications and broadcasting (often referred to as shortwave) rely on the ionosphere to propagate radio signals beyond the horizon. HF is a valuable alternative and complement to satellite communications, especially near the Earth's poles where geostationary satellites are not visible. The most prevalent (non-military) users of point-to-point HF communications are the aviation and shipping industries. The primary users of HF broadcasting are international broadcasters such as the BBC World Service.

The ionosphere is a dynamic propagation environment and this makes HF operations challenging even during routine space weather events. Solar activity, such as flares and coronal mass ejections, produce large variations in the radiation incident upon the Earth, which in turn lead to disturbances in the ionosphere:

- X-rays produced during solar flares cause an increase in the density of the lower layers of the ionosphere across the *sunlit* hemisphere. This increases the absorption (fading) of HF signals - an effect known as a sudden ionospheric disturbance (SIDS)
- highly energetic solar particles ionize the lower ionosphere in the *polar* regions. This increases the absorption of HF signals - an effect known as polar cap absorption (PCA)
- ionospheric storms occur, which result in *regional* and *global* reductions in the operational HF band.
- Storm associated electric fields and particles cause irregularities and gradients at high (primarily *auroral*) and at *equatorial* latitudes, between 18 local time and 24 local time These irregularities manifest themselves as multipath and Doppler distortion on HF signals and are related to scintillation seen at higher frequencies.

Modern HF systems provide substantial mitigation against all of these effects. These generally comprise digital modems (such as that defined in NATO STANAG 4415) that are tolerant to Doppler and multipath effects that can operate with low signal levels. Ideally, these modems are used in conjunction with multiple ground stations using multiple operating frequencies [*Goodman*, 2006; *Goodman et al.*, 1997]. However, there remain a large number of legacy systems – not least in commercial aircraft – that suffer frequent service interruptions during even moderate space weather events.

During a solar superstorm we expect the auroral oval to move south so that it includes or is south of the UK and consequently all of the above effects may be experienced by long distance HF communications originating in the UK. The effects will be worse in the evening hours, but will probably continue with little respite for several days.

Aircraft HF communications

As a minimum, aircraft are required to carry analogue voice equipment for long distance communications, although some aircraft are equipped with more modern and effective digital HF data links [*ARINC*, 2012]. Approximately 60% of aircraft flying out of the UK also carry satellite communications equipment in addition to their HF communication equipment. In contrast to some other countries (eg the US) no scheduled flights from the UK travel above 72° north. This renders the HF communications to UK aircraft somewhat less susceptible to moderate space weather events, although it should be noted that loss of HF communications to aircraft remains a frequent event even under normal conditions.

During an extreme event it is likely that communications to most aircraft in the North Atlantic would be lost. For aircraft in flight, there are well established procedures for coping with loss of HF communications, as defined by *ICAO* [2005]; these generally allow aircraft to complete their flight plans. However, in the event of an extended-duration, wide-area loss of HF communications to all aircraft (when satellite communications may also be lost, Section 12.5) it is likely that flights will be prevented from taking off. In this extreme case, there does not appear to be a defined mechanism for reopening airspace once communications have recovered.

HF broadcasting

HF broadcasting, such as that provided by the BBC World Service, will also be degraded or entirely unavailable for up to several days during an extreme space weather event. However, owing to the limited use of national HF broadcasting within the UK, this is unlikely to pose a major national threat.

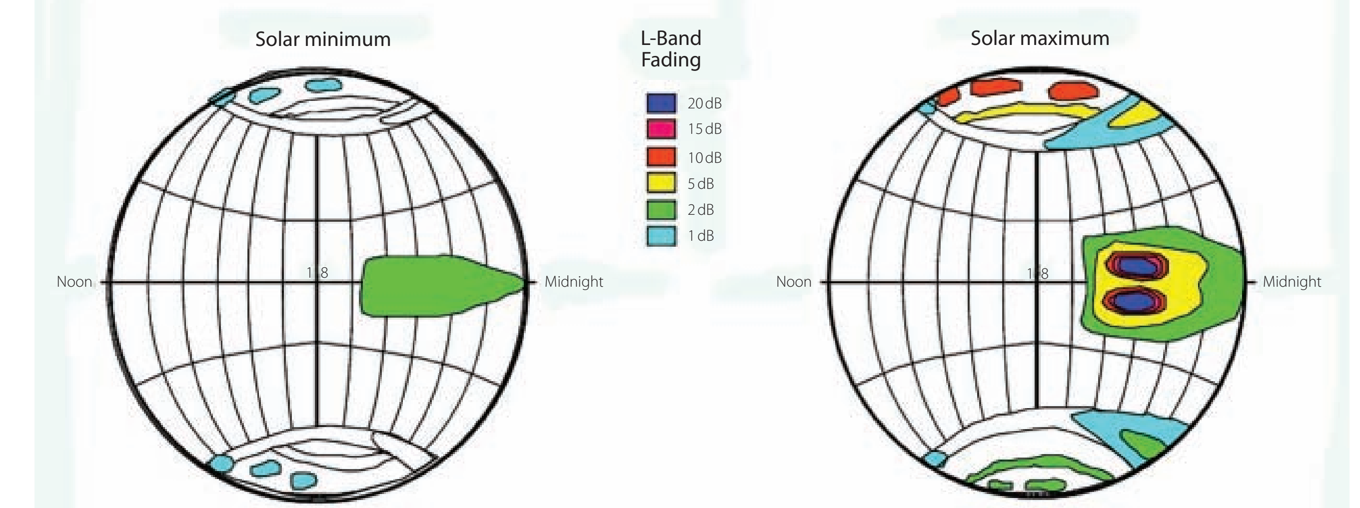


Figure 14. Ionospheric scintillation morphology © [Basu et al., 2002]

11.4 Mobile satellite communications

Small scale irregularities often found in the high and equatorial regions (*Figure 14*) during the evening hours cause scintillation, ie rapid fluctuations in the amplitude, phase and direction of arrival of signals of satellite signals. The effects of scintillation increase as the frequency is decreased and lead to increased error rates on communications signals. Moderate ionospheric scintillation generally only affects satellite communications operating in the VHF and low UHF band - such systems are largely military. More severe events can degrade L-band (~1.5GHz) civilian satellite communication systems (e.g. Iridium and Inmarsat).

Amplitude scintillation, leads to message errors if the system fade margin is exceeded; and if the fade is so long that the error correction code and interleaving is unable to correct the data steam. Fading has been recorded on satellite communication systems at 6 GHz although the fade depth at this frequency is only a few dB (peak-to-peak) and usually inconsequential. Fades of 10dB have been measured on 4 GHz signals (worst case) [*Aarons, 1984]* and over 20 dB has been observed at L band (1.5GHz) [*Basu et al.*, 1988]. This provides indicative values for a superstorm.

Solar radio bursts can interfere with VHF, UHF and L-band communications satellites. This is especially true for geostationary satellites around equinox, when the satellites lie close to the direction of the Sun (at certain times of day), and for mobile systems with large beamwidths and low signal-to-noise ratios [*Franke*, 1996].

During an extreme space weather event, high latitude scintillation will extend southwards to cover the UK and the equatorial scintillation will intensify and expand. Scintillation may occur at any time of the day, but will be strongest in the evening hours. Our judgement is that scintillation will render L-band links *largely* unavailable for between one and three days (section 11.1), however, this will be specific to the system.

For example, the L-band Iridium satellite network (which comprises a constellation of 66 LEO satellites operates with an average fade margin of 15.5 dB [*ICAO*, 2007] which is less than the 20dB fades measured by *Basu et al.* [1988]. It seems that even without an allowance for other degrading factors such as multipath, the fade margin is insufficient and signal outages will occur.

11.5 Satellite broadcasting

Assuming that the satellite survives the particle environment caused by an extreme space weather event, it is unlikely that services will be impaired. This is because satellite broadcasting operates at much higher frequencies than mobile satellite services (around 10 GHz). At these frequencies the ionosphere has little impact on the radio propagation.

11.6 Terrestrial broadcasting

Terrestrial radio (ie national and local broadcasting) should not be directly affected by space weather events. However, the secondary effects stemming from degraded timing from GPS should be considered; for example, the BBC DAB network operates as a single frequency network and uses GPS to provide time and frequency synchronisation [*ETSI*, 2000]. It is not clear how much holdover is provided by the system (see Section 11.3 for a discussion of timing holdover).

11.7 Communications – summary and recommendations

Terrestrial mobile communication networks

Summary

Good quality and reliable mobile (cellular) communications have become are relied on by the public. Furthermore, mobile communications are also critical for the delivery of effective police, fire and ambulance services and these services are likely to be in high demand during an extreme solar event when other parts of the national infrastructure are under stress.

This study has concluded that the UK's commercial cellular communications networks are currently much more resilient to the effects of a superstorm than those deployed in a number of other countries (including the US) since they are not reliant on GPS. Solar radio bursts have been identified as a potential problem, but only for parts of the network facing the Sun at dawn and dusk. The Academy believes that this is an acceptable risk given that each burst will only last ~20 minutes.

In contrast, the TETRA emergency communications network is dependent on GPS timing and, without mitigation strategies, would be vulnerable. However, a number of mitigation strategies are already in place.

Recommendations

- All terrestrial mobile communication networks with critical resiliency requirements should also be able to operate without GNSS timing for periods up to three days. This should particularly include upgrades to the network including those associated with the new 4G licenses where these are used for critical purposes and upgrades to the emergency services communications networks.

- Ofcom should consider including space weather effects when considering infrastructure resilience.

- The impact of extreme space weather events should be considered in the development of upgrades to emergency services communications networks and GNSS holdover should be ensured for up to three days.

- Further study of radio noise effects on mobile communication base stations should be undertaken to quantify the impact.

HF communications

HF communications are likely to be rendered inoperable for several days during a solar superstorm. HF communications are used much less than they used to be; however, they do provide the primary long distance communications bearer for long distance aircraft (not all aircraft have satellite communications and this may also fail during an extreme event). For those aircraft in the air at the start of the event, there are already well-defined procedures to follow in the event of a loss of communications. However, in the event of a persistent loss of communications over a wide area, it might be necessary to prevent flights from taking off. In this extreme case, there does not appear to be a defined mechanism for closing or reopening airspace once communications have recovered.

Recommendations

- The aviation industry and authorities should consider upgrades to HF modems (similar to those used by the military) to enable communications to be maintained in more severely disturbed environments. Such an approach could significantly reduce the period of signal loss during a superstorm and would be more generally beneficial.

- Operational procedures for closing and re-opening airspace in the event of an extended HF and satellite communications blackout should be developed

Mobile satellite communications

During an extreme space weather event, L-band satellite communications might be unavailable, or provide a poor quality of service, for between one and three days owing to scintillation. The overall vulnerability of L-band satellite communications to superstorm scintillation will be specific to the satellite system. For aviation users the operational impact on satellite communications will be similar to HF.

Recommendation

- Current and proposed L-band satellite communications used by the aviation and shipping industries should be assessed for vulnerability to extreme space weather.

Terrestrial broadcasting

Terrestrial broadcasting would be vulnerable to secondary effects, such as loss of power and GNSS timing.

Recommendation

- Where terrestrial broadcasting systems are required for civil contingency operations, they should be assessed for vulnerabilities to the loss of GNSS timing.

12. Conclusion

The report has sought to elucidate the nature and the impact of solar superstorms on contemporary and future high-technology systems with an emphasis on the UK. The breadth of technologies considered is significant and with the input of a number of domain experts, each has been studied in some depth. Our study is based on an estimate of the environmental impact of events which have occurred in the last 200 years. How representative these are of the longer term is not known, and in any case every solar superstorm is different.

The study has demonstrated that solar superstorms are indeed a risk to the UK's infrastructure. The UK electricity grid, while probably not as susceptible as in some other countries, is at risk and this provides the biggest concern because so much other infrastructure is dependent on it. Many other technologies are also vulnerable and the unmitigated impact is likely to have both safety-of-life and economic impacts. It appears that, in contrast to the USA and some other countries, contemporary UK 2G, 3G and 4G mobile communications networks are not vulnerable – this needs to be maintained. The study has not assessed how the impact of a superstorm might be magnified by the failure of multiple technologies, but the likelihood that this will indeed occur has been noted.

The Academy recommends continuing vigilance of this recently recognised threat. Vigilance will require the maintenance of current mitigation strategies and the development of new approaches in response to new technologies. Mitigation of the effects of solar superstorms requires a balance between engineering approaches and operational approaches – the latter being partly dependent on storm forecasts. The specific technology and the relative costs of mitigation will dictate the best way forward. Technological mitigation tends to be application specific, whereas forecasting has both generic and application specific elements. Reliable space weather forecasting requires a mix of satellite and ground based observations combined with coupled physical models. It is likely to be a Grand Challenge for the scientific community and requires partnership with the engineering and business communities to be effective.

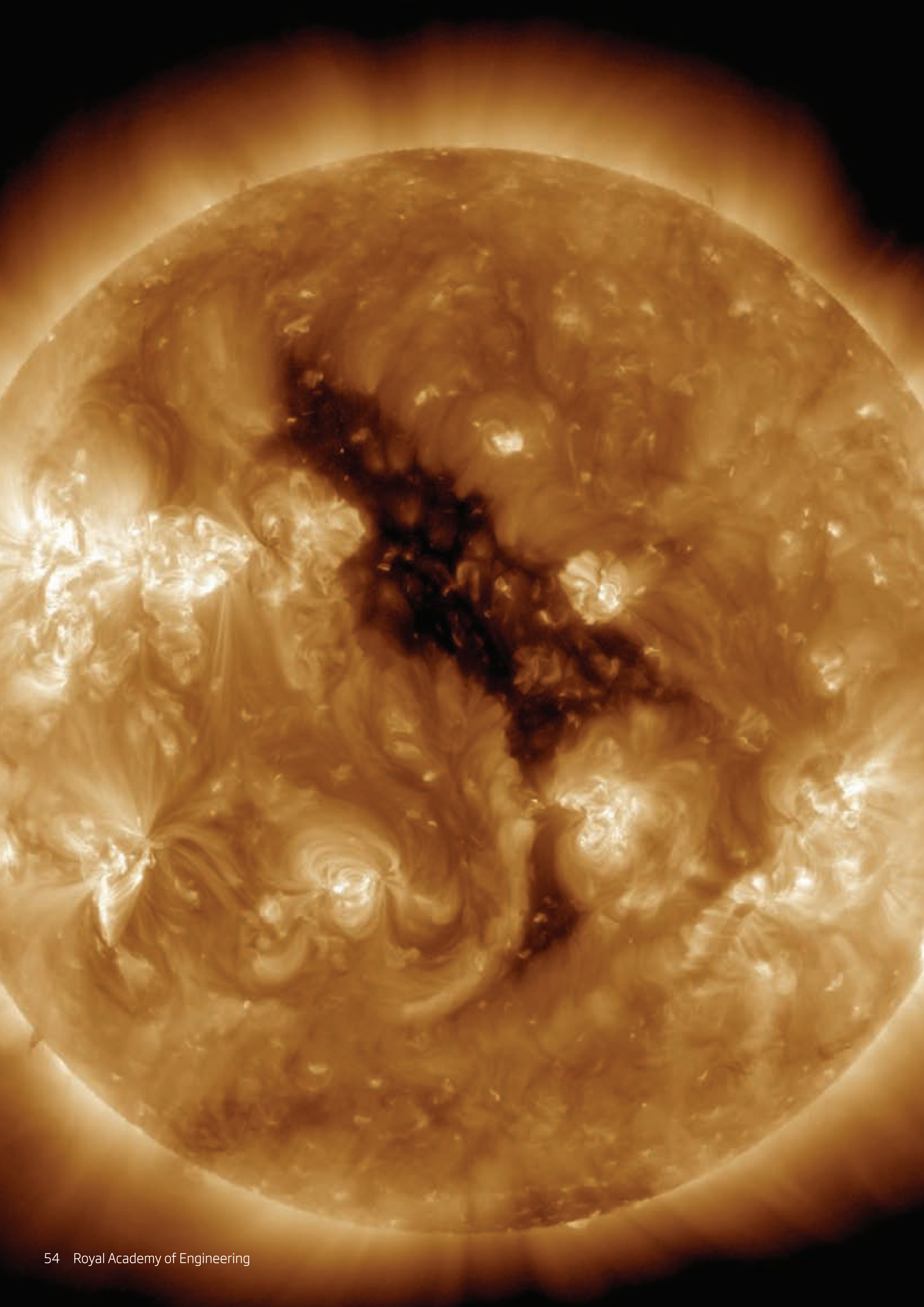
Technology specific recommendations have been included in each chapter of the report.

The Academy also recommends the initiation of a UK space weather board to provide overall leadership of UK space weather activities: observations and measurements, operational services, research and related technology developments. In regard to the latter the Board should, through its leadership, support and facilitate the UK space sector to enable it to respond to ESA and other space environment missions. The board, under the auspices of a nominated government department, should include representatives of all major stakeholders. It should be responsible for advising on proposal development and prioritisation, ensuring coherency of work programmes, avoiding duplication of projects and delivering value for money. Above all, the Board should link the research and operations communities so that the science is more clearly focused on delivering useful results and tested against well-defined metrics.

THE ACADEMY RECOMMENDS CONTINUING VIGILANCE OF THIS RECENTLY RECOGNISED THREAT. VIGILANCE WILL REQUIRE THE MAINTENANCE OF CURRENT MITIGATION STRATEGIES AND THE DEVELOPMENT OF NEW APPROACHES IN RESPONSE TO NEW TECHNOLOGIES.

Understanding and mitigating solar superstorms is a subject lying at the interface between science and engineering. The discipline has grown out of the former and, to maintain and extend our understanding and ability to measure and monitor space weather in general, and superstorms more particularly, it is vitally important to maintain the UK science expertise. Space weather research related to impacts on the Earth's environment, from the deep interior to the upper atmosphere and magnetosphere, is primarily the responsibility of the Natural Environment Research Council (NERC) while non-Earth space weather research, including space plasma and solar physics, are the responsibility of the Science and Technology Facilities Council (STFC). However, mitigating space weather and solar superstorms also has an important engineering dimension. Consequently, the Academy recommends that the Engineering and Physical Research Council (EPSRC) should ensure that its own programmes recognise the importance of extreme space weather mitigation and that EPSRC be fully integrated into any research council strategy.

This report presents our best assessment of the impact of a severe space weather event largely based on our experience of previous smaller events and our understanding of modern technology. We caution that the conclusions are subject to a large uncertainty as an extreme event has not been encountered in modern times and if it were there are likely to be many nonlinear dependencies. Therefore, our assessment may understate the impacts.



13. Bibliography

Aarons, J. (1984), Equatorial trans-ionospheric propagation conditions affecting digital communications, paper presented at Propagation Influences on Digital Transmission, NATO-AGARD, Electromagnetic Propagation Panel, Athens, Greece, 4-8 June.

Ahmed, O., R. Qahwaji, T. Colak, P. Higgins, P. Gallagher, and S. Bloomfield (2011), Solar Flare Prediction using Advanced Feature Extraction, Machine Learning, and Feature Extraction *Solar Physics, on-line first*, doi: 10.1007/s11207-011-9896-1.

Air Weather Service (1997), Space Environment Impacts on DoD operations, *Rep.37*.

Anderson, C. W., L. J. Lanzerotti, and C. G. MacLennan (1974), *Bell System Technical Journal*, *53*, 1817-1837.

ARINC (2012), GLOBALink, **www.arinc.com/products/globalink/index.html**

ATSB (2011), Transportation Safety Report, Aviation Occurrence Investigation AO-2008-070, Final, "In-flight upset 154 km west of Learmonth, WA 7 October 2008, VH-QPA, Airbus A330-303" *Rep.*

Baker, D. N. (2002), How to cope with Space Weather, *Science*, *297*, 1486, doi: 10.1126/science.1074956.

Baker, D. N., and J. L. Green (2011), The Perfect Solar Superstorm, *Sky and Telescope*, 28 February.

Baker, D. N., S. G. Kanekal, R. B. Horne, N. P. Meredith, and S. A. Glauert (2007), Low-altitude measurements of 2-6 MeV electron trapping lifetimes at 1.5< L<2.5, *Geophys. Res. Lett.*, *34*, 20, L20110, doi: 10.1029/2007gl031007.

Bala, B., L. J. Lanzerotti, D. E. Gary, and D. J. Thomson (2002), Noise in wireless systems produced by solar radio bursts, *Radio Sci.*, *37*, 2, 1018, doi: 10.1029/2001rs002481.

Barnard, L., and M. Lockwood (2011), A survey of gradual solar energetic particle events, *J. Geophys. Res.*, *116*, A05103, doi: 10.1029/2010JA016133.

Barnard, L., M. Lockwood, M. A. Hapgood, M. J. Owens, C. J. Davis, and F. Steinhilber (2011), Predicting space climate change, *Geophys. Res. Lett.*, *38*, L16103, doi: 10.1029/2011GL048489.

Opposite page: Coronal holes are regions where the sun's corona is dark. These features were discovered when X-ray telescopes were first flown above the Earth's atmosphere to reveal the structure of the corona across the solar disc. Coronal holes are associated with 'open' magnetic field lines and are often found at the sun's poles. The high-speed solar wind is known to originate in coronal holes © NASA

Basu, S., E. Mackenzie, and S. Basu (1988), Ionospheric constraints on VHF/UHF communications links during solar maximum and minimum period, *Radio Sci.*, *23*, 3, 363-378.

Basu, S., K. M. Groves, S. Basu, and P. J. Sultan (2002), Specification and forecasting of scintillations in communication/navigation links: current status and future plans, *Journal of Atmospheric and Solar-Terrestrial Physics*, *64*, 16, 1745-1754, doi: 10.1016/s1364-6826(02)00124-4.

Beamish, D., T. D. G. Clark, E. Clarke, and A. W. P. Thomson (2002), Geomagnetically induced currents in the UK: Geomagnetic variations and surface electric fields *J. Atmos. Sol. Terr. Phys.*, *64*, 1779-1792.

Blake, J. B., W. A. Kolasinski, R. W. Fillius, and E. G. Mullen (1992), Injection of electrons and protons with energies of tens of MeV into L < 3 on 24 March 1991, *Geophys. Res. Lett.*, *19*, 821-824.

Bolduc, L. (2002), GIC observations and studies in the Hydro-Québec power system, *J. Atmos. Sol. Terr. Phys.*, *64*, 1793-1802.

Boteler, D. H. (1977), Distributed-Source Transmission Line Theory for Electromagnetic Induction Studies. , paper presented at Supplement of the Proceedings of the 12th International Zurich Symposium and Technical Exhibition on Electromagnetic Compatibility, Zürich, Switzerland, February 18-20, 1997.

Boteler, D. H. (2006), The super storms of August/September 1859 and their effects on the telegraph system, *Adv. Space Res 38*, 159-172, doi: 10.1016/j.asr.2006.01.013.

Boteler, D. H., and G. J. van Beek (1999), August 4, 1972 revisited: A new look at the geomagnetic disturbance that caused the L4 cable system outage, *Geophys. Res. Lett.*, *26*, 5, 577-580, doi: 10.1029/1999GL900035.

Bradley, P. D., and E. Normand (1998), Single Event Upsets in Implantable Cardioverter Defribillators, *IEEE Trans. Nucl. Sci.*, *45*, 6, 2929-2940, doi: 10.1109/23.736549.

Butikofer, R., E. O. Fluckiger, L. L. Desorgher, and M. R. M.R. Moser (2008), The extreme solar cosmic ray particle event on 20 January 2005 and its influence on the radiation dose rate at aircraft altitude, *Science of The Total Environment*, *391*, 177-183.

Campbell, A., S. Buchner, E. Petersen, J. B. Blake, J. Mazur, and C. S. Dyer (2002), SEU measurements and predictions on MPTB for a large energetic solar particle event, *IEEE Trans. Nucl. Sci.*, *49*, 6, 1340-1344.

Cannon, P. S. (2009), Mitigation and Exploitation of the Ionosphere: A military perspective, *Radio Science*, *44*, RS0A20, doi: 10.1029/2008RS004021.

Carrano, C. S., C. T. Bridgwood, and K. M. Groves (2009), Impacts of the December 2006 solar radio bursts on the performance of GPS, *Radio Sci.*, *44*, RS0A25, doi: 10.1029/2008rs004071.

Cerruti, A. P., P. M. Kintner, D. E. Gary, L. J. Lanzerotti, E. R. de Paula, and H. B. Vo (2006), Observed solar radio burst effects on GPS/Wide Area Augmentation System carrier-to-noise ratio, *Space Weather*, *4*, 10, S10006, doi: 10.1029/2006sw000254.

Cerruti, A. P., P. M. K. Jr., D. E. Gary, A. J. Mannucci, R. F. Meyer, P. Doherty, and A. J. Coster (2008), Effect of intense December 2006 solar radio bursts on GPS receivers, *Space Weather*, *6*, S10D07, doi: 10.1029/2007SW000375.

Clark, S. (2007), *The Sun Kings: The Unexpected Tragedy of Richard Carrington and the Tale of How Modern Astronomy Began*, Princeton University Press.

Clauer, C. R., and G. e. Siscoe (2006), The Great Historical Geomagnetic Storm of 1859: A Modern Look, *Adv Space Res.*, *38*, 115-388.

Cliver, E. W., and L. Svalgaard (2004), The 1859 Solar–Terrestrial Disturbance and the current limits of Extreme Space Weather Activity, *Solar Physics*, *224*, 407-422.

Council of the European Union (1996), Directive 96/29/Euratom, laying down basic safety standards for the protection of health of workers and the general public against the dangers arising from ionising radiation, edited.

Curry, C. (2010), Dependency of Communications Systems on PNT Technology, *Rep.*, Chronos Technology Ltd, Stowfield Housem, Upper Stowfield, Lydbrook, Gloucestershire, GL17 9PD, UK.

Dunlop, M. W., Q.-H. Zhang, C.-J. Xiao, J.-S. He, Z. Pu, R. C. Fear, C. Shen, and C. P. Escoubet (2009), Reconnection at High Latitudes: Antiparallel Merging, *Phys. Rev. Lett.*, *102*, 075005.

Dyer, C. S., A. J. Sims, J. Farren, and J. Stephen (1990), Measurements of solar flare enhancements to the single event upset environment in the upper atmosphere, *IEEE Trans. Nucl. Sci.*, *37*, Dec, 1929-1937, doi: 10.1109/23.101211.

Dyer, C. S., K. Hunter, S. Clucas, and A. Campbell (2004), Observation of the solar particle events of October and November 2003 from CREDO and MPTB, *IEEE Trans. Nucl. Sci*, *51*, 6, 3388-3393, doi: 10.1109/TNS.2004.839156.

Dyer, C. S., F. Lei, A. Hands, and P. Truscott (2007), Solar particle events in the QinetiQ atmospheric radiation model, *IEEE Trans. Nucl. Sci*, *54*, 4, 1071-1075, doi: 10/1109/TNS.2007.893537.

Dyer, C. S., F. Lei, S. N. Clucas, D. F. Smart, and M. A. Shea (2003), Solar particle enhancements of single event effect rates at aircraft altitudes *IEEE Trans. Nucl. Sci.*, *50*, 6, 2038-2045, doi: 10.1109/TNS.2003.821375.

Edwards, R., E. Normand, and C. S. Dyer (2004), Technical standard for atmospheric radiation single event effects (SEE) on avionics electronics, paper presented at IEEE Radiation Effects Data Workshop Record, IEEE 04TH8774.

Erinmez, I. A., J. G. Kappenman, and W. A. Radasky (2002), Management of the geomagnetically induced current risks on the national grid company's electric power transmission system., *Journal of Atmospheric and Solar-Terrestrial Physics*, *64*, 5-6, 743-756.

Eroshenko, E. A., A. V. Belov, D. H. Boteler, S. P. Gaidash, S. L. Lobkov, R. Pirjola, and L. Trichtchenko (2010), Effects of strong geomagnetic storms on Northern railways in Russia, *Advances in Space Research*, *46*, 9, 1102-1110.

ETSI (2000), Digital Audio Broadcasting (DAB); Guidelines and rules for implementation and operation; Part 3: Broadcast network, edited.

FAA (2004), WAAS Performance Analysis Report, No 7 *Rep.*, FAA/William J. Hughes Technical Center, FAA.

Fazel, R., H. M. Krumholz, Y. Wang, J. S. Ross, J. Chen, H. H. Ting, N. D. Shah, K. Nasir, A. J. Einstein, and B. K. Nallamothu (2009), Exposure to Low-Dose Ionising Radiation from Medical Imaging Procedures, *New England Journal of Medicine*, *361*, 9, 849-857, doi: 10.1056/NEJMoa0901249.

Feynman, J., G. Spitale, J. Wang, and S. Gabriel (1993), Interplanetary Proton Fluence Model: JPL 1991, *J. Geophys. Res.*, *98*, 13281-13294.

Franke, E. (1996), Effects of Solar, Galactic and man-made noise on UHF SATCOM operation, paper presented at Militray Communications Conference, MILCOM 1996, IEEE.

Gaunt, C. T., and G. Coetzee (2007), Transformer failures in regions incorrectly considered to have low GIC-risk, paper presented at Power Tech, 2007, IEEE, Lausanne.

Getley, I. L., M. L. Duldig, D. F. Smart, and M. A. Shea (2005), Radiation dose along North American transcontinental flight paths during quiescent and disturbed geomagnetic conditions, *Space Weather*, *3*, 1, S01004, doi: 10.1029/2004sw000110.

Getley, I. L., L. G. I. Bennett, B. J. Lewis, B. Bennett, C. S. Dyer, A. D. P. Hands, and M. L. Duldig (2010), Evaluation of new cosmic radiation monitors designed for aircrew exposure assessment, *Space Weather*, *8*, 1, S01001, doi: 10.1029/2009sw000492.

Goodman, J. M. (2006), Telecommunication system vulnerabilities to space-weather events, paper presented at Third Symposium on Space Weather, American Meteorological Society January.

Goodman, J. M., J. Ballard, and E. Sharp (1997), A long-term investigation of the HF communication channel over middle- and high-latitude paths, *Radio Sci.*, *32*, 4, 1705-1715, doi: 10.1029/97rs01194.

Hapgood, M. A. (2011), Towards a scientific understanding of the risk from extreme space weather, *Adv. Space Res.*, *47*, 2059-2072, doi: 10.1016/j.asr.2010.02.007.

Health and Safety Executive (1999), The Ionising Radiations Regulations 1999, S.I. 1999 No. 3232. London, The Stationery Office Limited., edited.

Hernández-Pajares, M., J. M. Juan, J. Sanz, À. Aragón-Àngel, A. García-Rigo, D. Salazar, and M. Escudero (2011), The ionosphere: effects, GPS modeling and the benefits for space geodetic techniques, *J Geod*, doi: 10.1007/s00190-011-0508-5.

Horne, R. B. (2012), Forecasting the radiation belts in Europe, *Space Weather*, *10*, S008006, doi: 10.1029/2011JA017202.

HPA (2009), Application of the 2007 Recommendations of the ICRP to the UK, *Rep.RCE-12*, Health Protection Agency, UK.

IAEA (2011), Radiation Protection and Safety of Radiation Sources: International Basic Safety Standards (INTERIM EDITION), GSR Part 3 (Interim) General Safety Requirements, ISBN 978-92-0-120910-8, edited, International Atomic Energy Agency, Vienna.

ICAO (2005), North Atlantic minimum navigation performance specification (MNPS) airspace operations manual, edited, Published on behalf of the North Atlantic Systems Planning Group (NAT SPG) by the European and North Atlantic Office of ICAO.

ICAO (2007), Manual for ICAO aeronautical mobile satellite (route) service; Part 2-IRIDIUM, DRAFT v4.0, *Rep.*, ICAO.

ICAO (2010), **www2.icao.int/en/anb/met/iavwopsg/Space%20 Weather/Forms/AllItems.aspx**

ICRP (1991), 1990 Recommendations of the International Commission on Radiological Protection. ICRP, Publication 60, *Annals of the ICRP*, *21*, 1-3.

ICRP (2007), Recommendations of the International Commission on Radiological Protection. Publication 103, *Annals of the ICRP*, *37*, 2-4.

ICRP (2009), Application of the Commission's Recommendations for the Protection of People in Emergency Exposure Situations, ICRP Publication 109, *Annals of the ICRP 39*, 1.

ICRP (2012), 2012 ICRP Statement on Tissue Reactions and Early and Late Effects of Radiation in Normal Tissues and Organs - Threshold Doses for Tissue Reactions in a Radiation Protection Context, ICRP Publication 118, *Annals of the ICRP*, *41*, 1/2.

IEC (2008a), Process management for avionics – Atmospheric radiation effects – Part 5: Guidelines for assessing thermal neutron fluxes and effects in avionic systems, *Rep.IEC TS 62396-5*.

IEC (2008b), Process management for avionics – Atmospheric radiation effects – Part 4: Guidelines for designing with high voltage aircraft electronics and potential single event effects, *Rep.IEC TS 62396-4*.

IEC (2008c), Process management for avionics – Atmospheric radiation effects – Part 3: Optimising system design to accommodate the single event effects (SEE) of atmospheric radiation, *Rep.IEC TS 62396-3*.

IEC (2012a), Process management for avionics – Atmospheric radiation effects – Part 2: Guidelines for single event effects testing for avionics systems, *Rep.IEC 62396-2*.

IEC (2012b), Process management for avionics - Management plan - Part 1: Preparation and maintenance of an electronic components management plan, *Rep.IEC/TS 62239-1*.

IEC (2012c), Process management for avionics - Atmospheric radiation effects – Part 1: Accommodation of atmospheric radiation effects via single event effects within avionics electronic equipment, *Rep.IEC 62396-1 Ed.1*.

Iucci, N., et al. (2005), Space weather conditions and spacecraft anomalies in different orbits, *Space Weather*, *3*.

Joint Aviation Authorities (2001), JAR-OPS 1.390 Cosmic Radiation, edited.

Kahler, S. (2009), Variation of SEP event occurence with heliospheric magnetic field magnitudes, *Adv. Space Res.*, *43*, 1423–1428, doi: 10.1016/j.asr.2009.01.039.

Kaplan, E. (2005), *Understanding GPS: Principles and Applications*, Artech House.

Kappenman, J. (2010), Geomagnetic Storms and Their Impacts on the U.S. Power Grid, *Rep.*, Metatech Corporation.

Karsberg, A., G. Swedenborg, and K. Wyke (1959), The influences of earth magnetic currents on telecommunication lines, *Tele (English ed.), Televerket, Stockholm, 1-21*.

Kintner, P. M., Jr., B. O'Hanlon, D. E. Gary, and P. M. S. Kintner (2009), Global Positioning System and solar radio burst forensics, *Radio Sci.*, *44*, RS0A08, doi: 10.1029/2008rs004039.

Koons, H. C., and J. F. Fennell (2006), Space weather effects on communications satellites,, 316, March, *The Radio Science Bulletin, International Union of Radio Science (URSI)*, *316*, 27-41.

Koons, H. C., J. E. Mazur, R. S. Selesnick, B. J. B, J. F. Fennell, J. L. Roeder, and P. C. Anderson (1999), The Impact of the Space Environment on Space Systems *Rep.TR-99 (1670)-1*, Aerospace Corporation, El Segundo, USA.

Lantos, P., and N. Fuller (2003), History of the solar particle event radiation doses on-board aeroplanes using a semi-empirical model and Concorde measurements *Radiation Protection Dosimetry*, *104*, 3, 199-210.

Lanzerotti, L. J. (1992), Comment on "Great magnetic storms" by Tsurutani et al, *Geophys. Res. Lett.*, *19*, 19, 1991-1992, doi: 10.1029/92gl02238.

Lanzerotti, L. J., L. V. Medford, C. G. Maclennan, J. S. Kraus, J. Kappenman, and W. Radasky (2001), Trans-Atlantic geopotentials during the July 2000 solar event and geomagnetic storm, *Solar Physics*, *204*, 351-359, doi: 10.1023/A:1014289410205.

Laurenza, M., E. W. Cliver, J. Hewitt, M. Storini, A. G. Ling, C. C. Balch, and M. L. Kaiser (2009), A technique for short-term warning of solar energetic particle events based on flare location, flare size, and evidence of particle escape, *Space Weather*, *7*, S04008.

Lindborg, L., D. T. Bartlett, P. Beck, I. R. McAulay, K. Schnuer, H. Scraube, and F. Spurny (2004.), Compilation of measured and calculated data, edited, A report of EURADOS WG5.

Lockwood, M., M. J. Owens, L. Barnard, C. J. Davis, and S. Thomas (2012), Solar Cycle 24: what is the Sun up to?, *Astronomy & Geophysics*, *53*, 3.9-3.15.

Lyons, D. (2000), Sun Screen, **www.forbes.com/global/2000/1113/0323026a.html**

Maehara, H., T. Shibayama, S. Notsu, Y. Notsu, T. Nagao, S. Kusaba, S. Honda, D. Nogami, and K. Shibata (2012), Superflares on solar-type stars, *Nature*, *485*, 478-481, doi: 10.1038/nature11063.

Mannucci, A. J., B. A. Iijima, U. J. Lindqwister, X. Pi, L. Sparks, and B. D. Wilson (1999), GPS and Ionosphere, paper presented at Reviews of Radio Science 1996-1999, Oxford Science Publications.

McColl, N. P., and S. L. Prosser (2001), Emergency data handbook, *Rep. NRPB-W-19*, National Radiological Protection Board, Chilton, UK.

McCracken, K., G. Dreschhoff, E. J. Zeller, D. Smart, and M. Shea (2001), Solar cosmic ray events for the period 1561–1994: 1. Identification in polar ice 1561–1950, *J. Geophys. Res.*, *106*, 21,585–521,598, doi: 10.1007/s11207-005-5257-2.

Medford, L. V., L. J. Lanzerotti, J. S. Kraus, and C. G. Maclennan (1989), Transatlantic Earth Potential Variations During the March 1989 Magnetic Storms, *Geophys. Res. Lett.*, *16*, 10, doi: 10.1029/GL016i010p01145.

Melott, A.L. and Thomas, B.C. (2012) Brief communication: Causes of an AD 774-775 14C increase, *Nature 491*, E1-E2, doi:10.1038/nature11695

Miyake, F., K. Nagaya, K. Masuda, and T. Nakamura (2012), A signature of cosmic-ray increase in AD 774–775 from tree rings in Japan, *Nature*, *486*, 240-242, doi: 10.1038/nature11123.

NASA (2012), NASA STEREO Observes One of the Fastest CMEs On Record, **www.nasa.gov/mission_pages/stereo/news/fast-cme.html**

NASA GSFC (2012), Space Environment Testbeds Overview, **www.lws-set.gsfc.nasa.gov/radiation_model_user_forum.html**

NERC (2010), High-Impact, Low-Frequency Event Risk to the North American Bulk Power System, *Rep.,* North American Electric Reliability Corporation.

NERC (2012), Effects of Geomagnetic Disturbances on the Bulk Power System, *Rep.*, North America Electric Reliability Corporation.

Normand, E. (1996), Single Event Upset at Ground Level, *IEEE Trans. Nucl. Sci.*, *43*, 6, 2742-2750, doi: 10.1109/23.556861.

Normand, E. (2001), Correlation of In-flight Neutron Dosimeter and SEU Measurements with Atmospheric Neutron Model, *IEEE Trans. Nucl. Sci.*, *48*, 6, 1996-2003, doi: 10.1109/23.983162.

Normand, E., J. L. Wert, D. L. Oberg, P. R. Majewski, P. Voss, and S. A. Wender (1997), Neutron-Induced Single Event Burnout in High Voltage Electronics, *IEEE Trans. Nucl. Sci*, *44*, 6, 2358-2366, doi: 10.1109/23.659062.

NRC (2008), Severe Space Weather Events - Understanding Societal and Economic Impacts. A Workshop Report, *Rep.*, National Academy of Sciences, Washington DC.

Núñez, M. (2011), Predicting solar energetic proton events (E > 10 MeV) *Space Weather*, *9*, S07003, doi: 10.1029/2010SW000640.

Odenwald, S., J. Green, and W. Taylor (2006), Forecasting the impact of an 1859-calibre superstorm on satellite resources, *Adv. In Space Res.*, *38*, 280-297.

Olsen, J., P. E. Becher, P. B. Fynbo, P. Raaby, and J. Schultz (1993), Neutron-Induced Single Event Upsets in Static RAMs Observed at 10 km Flight Altitude, *IEEE Trans. Nucl. Sci.*, *40*, 77.

ONS (2012), Leading Causes of Death in England and Wales, 2009, **www.ons.gov.uk/ons/taxonomy/index.html?nscl=Causes+of+Death**

Posner, A. (2007), Up to 1-hour forecasting of radiation hazards from solar energetic ion events with relativistic electrons, *Space Weather*, *5*, S05001, doi: 10.1029/2006SW000268.

Price, P. R. (2002), Geomagnetically induced current effects on transformers, *IEEE Transactions on Power Delivery*, *17*, 4, 1002-1008.

Ptitsyna, N. G., V. V. Kasinskii, G. Villoresi, N. N. Lyahov, L. I. Dorman, and N. Iucci (2008), Geomagnetic effects on mid-latitude railways: A statistical study of anomalies in the operation of signaling and train control equipment on the East-Siberian Railway, *Advances in Space Research*, *42*, 9, 1510-1514.

Pulkkinen, A., M. Hesse, S. Habib, L. V. d. Zel, B. Damsky, F. Policelli, D. Fugate, and W. Jacobs (2009), Solar Shield - forecasting and mitigating space weather effects on high-voltage power transmission systems *Natural Hazards*, doi: 10.1007/s11069-009-9432-x.

Reames, D. (1999), Particle acceleration at the Sun and in the heliosphere, *Space Sci. Rev.* , *90*, 413-491, doi: 10.1023/A:1005105831781.

Riley, P. (2012), On the probability of occurrence of extreme space weather events, *Space Weather*, *10*, S02012, doi: 10.1029/2011SW000734.

Ryden, K. A., P. A. Morris, and A. D. P. Hands (2008), Radiation monitoring in Medium Earth Orbit over the Solar minimum period, paper presented at Proc. RADECS 2008, Jyvaskyla, Finland, 10-12 September.

Satellite News Digest (2012), Satellite Outages and Failures, edited.

SEIEG (2012), Summary of space weather worst-case environments, Edited M Hapgood, *Rep.RAL-TR-2012-022,* **http://epubs.stfc.ac.uk/**, Rutherford-Appleton Laboratory

Shprits, Y., D. Subbotin, B. Ni, R. H. Horne, D. N. Baker, and P. Cruce (2011), Profound change of the near-Earth radiation environment caused by solar superstorms, *Space Weather*, *9*, 8, S08007, doi: 10.1029/2011sw000662.

Sims, A. J., C. S. Dyer, C. L. Peerless, K. Johansson, H. Pettersson, and J. Farren (1994), The Single Event Upset Environment for Avionics at High Latitude, *IEEE Trans. Nucl. Sci.*, *41*, 6, 2361-2367, doi: 10.1109/23.340588.

Small Cell Forum (2012), Femtocell Synchronisation and Location, Report 036, at **www.smallcellforum.org/resources-white-papers**

Stenquist, D. (1914), *The Magnetic Storm of Sept. 25, 1909*, Republished 2010 by Nabu Press.

Taktakishvili, A., P. MacNeice, and D. Odstrcil (2010), Model uncertainties in predictions of arrival of coronal mass ejections at Earth orbit,, *Space Weather*, *8*, S06007, doi: 10.1029/2009SW000543.

Thomson, A. W. P., E. B. Dawson, and S. J. Reay (2011), Quantifying extreme behavior in geomagnetic activity, *Space Weather*, *9*, S10001, doi: 10.1029/2011SW000696.

Thomson, A. W. P., A. J. McKay, E. Clarke, and R. S. J. (2005), Surface electric fields and geomagnetically induced currents in the Scottish Power grid during the 30 October 2003 geomagnetic storm, *Space Weather*, *3*, S11002, doi: 10.1029/2005SW000156.

Trichtchenko, L., and D. H. Boteler (2001), Specification of geomagnetically induced electric fields and currents in pipelines, *J. Geophys. Res.*, *106*, A10, 21039–21048, doi: 10.1029/2005JA011294.

Tsurutani, B. T., W. D. Gonzalez, G. S. Lakhina, and S. Alex (2003), The extreme magnetic storm of 1–2 September 1859, *J. Geophys. Res.*, *108*, A7, 1268, doi: 10.1029/2002ja009504.

Turnbull, K. (2011), Space Weather Hazards to the United Kingdom's National Grid, PhD thesis, University of Lancaster, UK.

Underwood, C. I. (1996), Single Event Effects in Commercial Memory Devices in the Space Radiation Environment, PhD thesis, University of Surrey, Guildford.

Vette, J. I. (1991), The AE-8 trapped electron model environment, *Rep.*, National Space Science Data Center (NSSDC), World Data Center A for Rockets and Satellites (WDC-A-R&S), National Aeronautics and Space Administration, Goddard Space Flight Center.

Wall, B. F., R. Haylock, J. T. M. Jansen, M. C. Hillier, and D. Hart (2011), Radiation risks from medical x-ray examinations as a function of age and sex of patient., *Rep.HPA-CRCE-028*, Health Protection Agency, Chilton, UK.

Walter, T., A. Hansen, J. Blanch, and P. Enge (2000), Robust Detection of Ionospheric Irregularities, paper presented at Institute of Navigation's GPS conference, Salt Lake City, UT, USA.

Watson, S. J., A. L. Jones, W. B. Oatway, and J. S. Hughes (2005), Ionising radiation exposure of the UK population, *Rep.HPA-RPD-001*, Health Protection Agency, Chilton, UK.

Weaver, M., W. Murtagh, C. Balch, D. Biesecker, L. Combs, M. Crown, K. Doggett, J. Kunches, H. Singer, and D. Zezula (2004), Halloween Space Weather Storms of 2003, *Rep.NOAA Technical Memorandum OAR SEC-88*, NOAA.

Wik, M., R. Pirjola, H. Lundstedt, A. Viljanen, P. Wintoft, and A. A. Pulkkinen (2009), Space weather events in July 1982 and October 2003 and the effects of geomagnetically induced currents on Swedish technical systems., *Annales Geophysicae*, *27*, 4, 1775-1787.

Wolff, E. W., M. Bigler, M. A. J. Curran, J. E. Dibb, M. M. Frey, M. Legrand, and J. R. McConnell (2012), The Carrington event not observed in most ice core nitrate records, *Geophys. Res. Lett.*, *39*, L08503, doi: 10.1029/2012GL051603.

Ziegler, J. F., et al. (1996), IBM experiments in soft fails in computer electronics (1978-1994), *IBM Journal of Research and Development*, *40*, 1, 3-18.

14. Glossary

Term	Definition
Bastille Day event	Radiation storm that occurred on 14 July 2000 and associated geomagnetic storm on 15/16 July
Carrington event	The largest solar storm on record. It took place from 1-3 September 1859 and is named after British astronomer Richard Carrington.
Coronal mass ejection	A large burst of solar wind plasma ejected into space
Coronagraph	An instrument for observing and photographing the Sun's corona, consisting of a telescope fitted with lenses, filters, and diaphragms that simulate an eclipse
Electrostatic discharge	The sudden flow of electricity between two objects caused by contact, an electrical short or dielectric breakdown
eLoran	Enhanced Long-Range Navigation System
Geo-effective	Storm-causing
Geomagnetically induced currents	Electrical currents flowing in earthed conductors, induced by rapid magnetic field changes
Geomagnetic storm	A worldwide disturbance of the Earth's magnetic field induced by a solar storm
Geostationary orbit	A circular orbit 35,900 km above the Earth's surface where most telecommunications satellites are located. Satellites in GEO orbit appear stationary relative to the rotating Earth
Global navigation satellite systems	Generic term for space-based navigation systems of which GPS and Galileo are examples
Halloween event	A solar storm that occurred in October 2003
Interplanetary magnetic field	Solar magnetic field carried by the solar wind to the planets and beyond
Ionosphere	The region of the atmosphere between around 80-600 km above the Earth
L1 Langrangian point	The point where the gravitational forces of the Sun and Earth balance
Magnetosphere	The region surrounding a planet, such as the Earth, in which the behaviour of charged particles is controlled by the planet's magnetic field
Magnetometer	An instrument used to measure the strength and direction of magnetic fields.
Radiation hardening	The making of electronic systems and their components resistant to damage caused by ionising radiation
Reactive power	Describes the energy in the magnetic component of the alternating current
Relativistic	Having or involving a speed close to that of light
Scintillation	The perturbation of radio signals caused by variations in the ionosphere
Solar corona	The extended outer atmosphere of the Sun
Solar energetic particles	High-energy particles coming from the Sun
Solar flare	A brief powerful eruption of particles and intense electromagnetic radiation from the Sun's surface
Solar wind	The constant stream of charged particles, especially protons and electrons, emitted by the Sun at high velocities, its density and speed varying during periods of solar activity
Substorm	A brief disturbance of the Earth's magnetosphere that causes energy to be released from its "tail"
TETRA	An emergency communications network
Thermosphere	An atmospheric layer lying between the mesosphere and the exosphere, reaching an altitude of ~750km above the Earth's surface

15. Abbreviations and acronyms

Acronym	Meaning
3GPP	Third Generation Partnership Project
A-GPS	Assisted GPS
APNT	Alternate Position Navigation and Time
BGS	British Geological Survey
CDMA	Code division multiple access
CME	Coronal mass ejection
COTS	Commercial off the shelf
Cs	Caesium (Atomic frequency standard)
CSAC	Chip scale atomic clock
DECC	Department of Energy and Climate Change
DME	Distance measuring equipment
DRAM	Dynamic random access memory
Dst	A geomagnetic index
E3C	Energy Emergencies Executive Committee
ECSS	European Cooperation of Space Standardisation
EGNOS	European Geostationary Navigation Overlay Service
eLoran	Enhanced long range navigation
EMC	Electromagnetic compatibility
EPSRC	Engineering and Physical Sciences Research Council
ESA	European Space Agency
ESD	Electrostatic discharge
ETSI	European Telecommunications Standards Institute
FAC	Field aligned currents
FAA	Federal Aviation Administration
FCC	Federal Communications Commission
FDD	Frequency division duplex
GCR	Galactic cosmic rays
GEO	Geostationary orbit
GIC	Geomagnetically induced currents
GLE	Ground level event
GLONASS	GLObal NAvigation Satellite System - GLObalnaya NAvigatsionnaya Sputnikovaya Sistema) A satellite-based radio navigation system
GMD	Geomagnetic disturbance
GNSS	Global Navigation Satellite Systems

GPS	Global Positioning System
GSP	Grid supply point
HANE	High altitude nuclear events
HF	High frequency
HSPA	High speed packet access
ICAO	International Civil Aviation Organisation
ICRP	International Commission on Radiological Protection
IEC	International Electrotechnical Commission
IECQ	International Electrotechnical Commission Quality Assessment System for Electronic Components
IEEE	Institute of Electrical and Electronic Engineers
IEEE-1588	Packet timing standard for Ethernet
IMF	Interplanetary magnetic field
ITU	International Telecommunications Union
LEO	Low Earth orbit
LTE	Long term evolution
LTE-A	Long term evolution – advanced
MBU	Multiple bit upset
MCU	Multiple cell upset
MEO	Medium Earth orbit
MHD	Magneto-hydrodynamic
MSCs	Mechanically switched compensators
MTBF	Mean time between failures
MTTR	Mean time to repair
NERC	Natural Environment Research Council
NOAA	National Oceanic and Atmospheric Administration
NRA	National risk assessment
NTP	Network time protocol
OCXO	Oven controlled crystal oscillator
PCA	Polar cap absorption
PDV	Packet delay variation
PNT	Positioning, navigation and timing
PRC	Primary reference clock
PTPv2	Precision time protocol v2 (IEEE-1588-2008)
Rb	Rubidium (atomic clock)

SAE	Society of Automotive Engineers
SBAS	Satellite based augmentation systems
SDH	Synchronous digital hierarchy
SEB	Single event burnout
SEE	Single event effects
SEFI	Single event functional interrupt
SEGR	Single event gate rupture
SEIEG	Space Environment Impact Expert Group
SEL	Single event latchup
SEP	Solar energetic particle
SET	Single event transient
SEU	Single event upset
SFU	Solar flux unit
SGT	Super grid transformer
SIDS	Sudden ionospheric disturbances
SIRs	Stream interaction regions
SRAM	Static random access memory chip
SRB	Solar flare solar radio burst
SSU	Synchronisation source utility
SVCs	Static variable compensators
SyncE	Synchronous Ethernet
TCP/IP	Transmission control protocol/internet protocol
TCXO	Temperature compensated crystal oscillator
TDD	Time division duplex
TD-LTE	TDD variant of LTE technology
TDM	Time division multiplex
TETRA	Terrestrial European trunked radio access
UHF	Ultra high frequency
UTC	Universal coordinated time
VHF	Very high frequency
VoIP	Voice over internet protocol
WAAS	US wide area augmentation system

Appendix: Authors

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Notes

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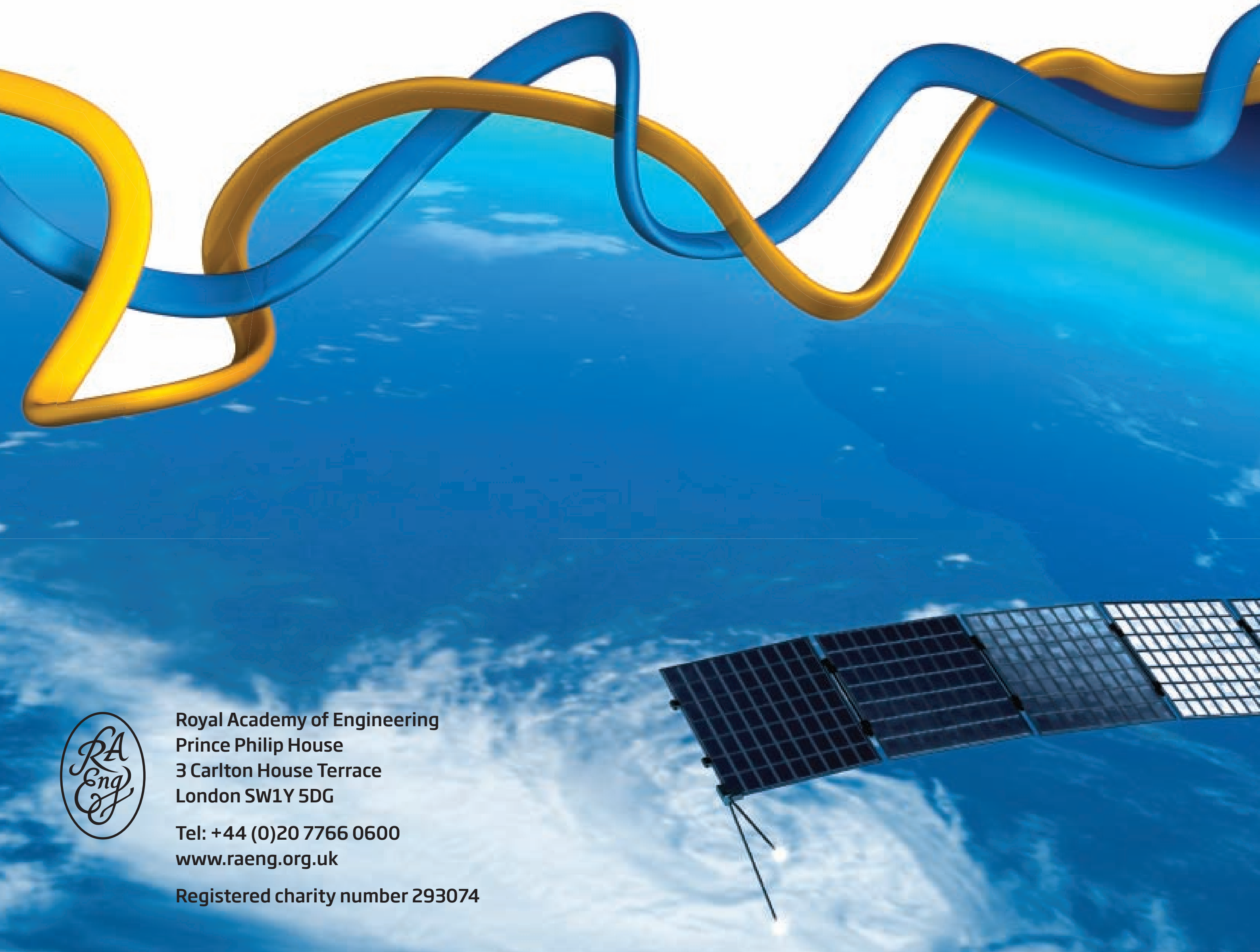

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